VALIDATING AND IMPROVING THE CANADIAN COAST GUARD SEARCH AND RESCUE PLANNING PROGRAM (CANSARP) OCEAN DRIFT THEORY

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Validating and Improving the Canadian Coast Guard Search and Rescue Planning Program (CANSARP) Ocean Drift Theory

by

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Abstract

The Canadian Coast Guard Search and Rescue Coordinator uses a software system to estimate the drift of targets in the ocean, and consequently determine a search area. Existing software applies a simple drift algorithm (MiniMax) that has been in use since World War II (Canadian Coast Guard/Department of Fisheries and Oceans Canada [CCG/DFO], 2000).

The Coast Guard must be aware of the effectiveness of the drift prediction algorithm, and the efficiency of the environmental inputs used. This thesis determines the practicality of the available methods of MiniMax and the stochastic Monte Carlo approach. In addition, we explore the implementation of higher resolution ocean and sea current inputs. This both improves the current MiniMax algorithm and allows exploration of a modified Monte Carlo approach.

Using an assembled database of drifting buoys in the North Atlantic Ocean, the accuracy of the MiniMax and the Norwegian Meteorological Office implementation of the Monte Carlo methods are evaluated. Results from the assessment indicate that present prediction methods in CANSARP underestimate actual drifts by 2 to 3 times the actual length. These results are used to determine where improvements must be made to the current algorithms and environmental inputs for eventual application to the search system.

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Contents

Abstract .... *ii*

Acknowledgements .... *iii*

Contents .... *iv*

List of Tables .... *vi*

List of Figures .... *vii*

List of Abbreviations and Symbols .... *xi*

Chapter 1 Introduction *1*

1.1 An Overview of Search and Rescue **1**

1.2 Background on the Canadian Coast Guard Search and Rescue Planning Program (CANSARP) Software **2**

1.3 Inputs for Search and Rescue Planning **4**

1.3.1 Last Known Position 4
1.3.2 Leeway 5
1.3.3 Ocean Currents in CANSARP 6
1.3.4 Observed (Measured) Currents 7
1.3.5 Ocean Forecast Models 8
1.3.6 Subjective Currents 10
1.3.7 Wind Currents 10
1.3.8 Tidal Currents 10
1.3.9 Sea Current 11

1.4 Search Planning Summary **11**

1.5 United States Coast Guard (USCG) Model **12**

1.6 Norwegian Search and Rescue Model **15**

1.7 Thesis Objective **19**

Chapter 2 Environmental Data Sets *21*

2.1 Climatological Currents **21**

2.2 Mercator Currents **22**

2.3 CNOOFS Currents **23**

2.4 Canadian Meteorological Centre Forecast Winds **24**

2.5 Self-Locating Datum Marker Buoys (SLDMBs) **26**

2.6 World Ocean Circulation Experiment (WOCE) Drifters **27**

2.7 Drifter Use **29**

Chapter 3 Drift Algorithms *43*

3.1 The MiniMax Method in Canada **43**

3.2 The Monte Carlo Method **46**

3.3 Drift Method Applications in CANSARP Scientific **49**

3.3.1 Wind Driven Component Calculation Options 49

3.4 Additional Current Approximation Algorithm: The Pollard-Millard Method **53**

Chapter 4 Validation of Environmental Inputs and Current Estimation Algorithms ***55***

Chapter 5 Exploring Issues and Possible Change for CANSARP Scientific ***68***

5.1 Drift Prediction Length Issue **68**

5.1.1 Current Velocity Comparison at Depths 68

5.1.2 Radius Determination 74

5.2 Optimizing the Number of Particles used in the Monte Carlo Method **76**

5.3 Case Study: The Kiel Mooring **79**

5.4 Analysis of Errors Produced by CANSARP Scientific **87**

Chapter 6 Conclusions ***91***

References ***95***

Appendix A Running Cansarp Scientific ***A-1***

Select CANSARP Settings A-1

Select Current Settings A-2

Select Wind Settings A-3

Update Path Settings A-4

Running a Simulation A-5

Appendix B Changes Made to the Monte Carlo Method in CANSARP Scientific .. ***B-1***

Appendix C General Changes Made to CANSARP Scientific ***C-1***

List of Tables

Table 1 *Available Configurations of Output Data from Mercator Model* 23

Table 2 *Drifter Data and Sources with Contact Names* 30

Table 3 *Mean and Standard Deviation of Drift Length for 12 SLDMBs in August 2007 Using Current Estimation Methods Compared to Actual SLDMB Drift Length* 51

Table 4 *Data from Monte Carlo Simulations over 48 Hours with SLDMB 17324 with Mercator Currents and Varying Numbers of Particles* 77

List of Figures

Figure 1.1 *Sample data transfer from a drifting buoy to CANSARP from deployment to the point that it is usable in CANSARP for search planning.* *8*

Figure 1.2 *Delineations of model boundaries used in CANSARP a) Bathymetry of the Gulf of Saint Lawrence and a subset of the IML Model Boundaries in upper left panel. b) The Grand Banks model geographical boundries delineated by the blue line.* *9*

Figure 1.3 *Example of a convex hull plotted around points ranging between 2 and 8 in both the x and y axis. Note that the figure is formed by outlining the outermost points from the cluster of particles.* *18*

Figure 2.1 *Climatological sea currents for a) Summer and b) Winter as used in CANSARP Scientific. Coastline and bathymetry displayed to provide reference. Quivers shown are reduced such that 1/9 of all quivers on grid are displayed.* *22*

Figure 2.2 *The air or sea deployable Self Locating Datum Marker Buoy (SLDMB) is composed of an air-deployable buoy, a GPS receiver, and an ARGOS satellite data transmitter (http://www.seimac.com/).* *27*

Figure 2.3 *Comparison of amount of available drifter data between -90° and -30° west, 25° and 80° north. From this plot it is apparent that the GTS data from MEDS has a vast supply of drifters, while the SLDMBs are lacking.* *31*

Figure 2.4 *Number of observed drifter data per squared kilometer for available timeframes for: a) MEDS GTS 2001-2007 b) MEDS Raw 1994-2002 c) MEDS P&S 1989-2003 and d) SLDMBs 1999-2007. Note varying density scales for plots.* *33*

Figure 2.5 *a) SLDMBs on Newfoundland shelf deployed in August of 2007. Each SLDMB is a represented by a different color and entire life spans are illustrated. Bathymetry lines are labeled and numbered in meters. b) All available MEDS GTS drifters in the Northewest Atlantic for August 2007.* *35*

Figure 2.6 *Mean velocity comparison between a) SLDMB and b) GTS drifters over their respective lifespans. Each dot represents one drifting buoy.* *36*

Figure 2.7 *a) Distances of total drifts of 12 SLDMBs from August 2007 for 48 hours on the Newfoundland Shelf (blue) with mean length of 70 km along with predicted CNOOFS trajectories (red) with mean length 22 km and predicted Mercator trajectories (blue) with mean length 26 km. b) Both current types under calculate the total distance of SLDMB trajectories. The difference in SLDMB and CNOOFS (magenta) plot has a mean of 48 km and the difference between SLDMB and Mercator (cyan) plot has a mean of 44 km. These lines are always positive indicating that the SLDMB trajectory is always longer.* *37*

Figure 2.8 *CANSARP Scientific simulations with MinMax Method using both CNOOFS (top panels) and Mercator (bottom panels) currents at levels closest to surface (left) and 15 m (right) on the Newfoundland Shelf over 48 hours for SLDMB 17324. Blue lines represent the drifter trajectory while the black line is the predicted trajectory. Black circles indicate the search area. While some improvement is seen in total distance, resolution of drift is lost and* *distance is still far under calculated for all 12 cases of SLDMBs in August 2007 (by about 3 times at the surface and about 5 times at 15 m for CNOOFS currents; 2.7 times for Mercator currents at the surface, and about 2.6 times at 15 m.) This figure illustrates a unique case in the Labrador Current where the Mercator currents almost match the SLDMB trajectory.* *38*

Figure 2.9 *CANSARP Scientific simulations with MiniMax Method using both CNOOFS and Mercator Currents at levels closest to surface and 15 m off the Newfoundland shelf over 48 hours. While some improvement is seen in total distance, resolution of drift is lost and distance is still far under calculated, as specified in Figure 2.8.* *39*

Figure 2.10 *Correlation between distance of CANSARP Scientific output using Mercator Currents at surface level and 15 m versus actual drift trajectories. No obvious patterns can be observed geographically.* *40*

Figure 2.11 *Continuous and discontinuous CNOOFS model output data used in CANSARP Scientific simulations. Top images show simulations with continuous data while bottom images show simulations with discontinuous data.* *42*

Figure 3.1 *The MiniMax Method basic diagram.* *45*

Figure 3.2 *Example Monte Carlo Simulation in CANSARP Scientific with CNOOFS currents for 48 hours using 250 particles (green dots). The dashed green line is the predicted search area by the Monte Carlo method, the solid pink lines are the predicted search trajectory by CANSARP Scientific (mean of left and right clouds of particles), and the solid blue line is the actual SLDMB trajectory. The numbered line is a line of bathymetry at 200 m depth*...*48*

Figure 3.3 *Rule of Thumb (black circles), Ekman (red circles), and Madsen (green circles) current estimation algorithm outputs as they exist in CANSARP Scientific on 12 SLDMBs from August 2007 over 48 hours. Blue lines are SLDMB tracks punctuated by a green dot at the start and a red dot at the end of the drift. Actual positions relative to landmasses and bathymetry can be seen in Figure 2.5a.* *52*

Figure 3.4 *Sample Pollard Millard Simulations for 48 hours with SLDMBs 17316 and 17326. Blue lines are SLDMB tracks while black lines and circles represent the predicted Pollard Millard trajectory and search area, respectively. Predicted trajectories are 2 to 3× shorter than actual trajectories.* *54*

Figure 4.1 *Rule of Thumb, Ekman, and Madsen current estimation methods with wind V = 10 m/s and U = 0 m/s. Methods illustrate calculated trajectory velocities of 0.328 m/s, 0.2148 m/s and 0.2662 m/s, respectively.* *56*

Figure 4.2 *a) CNOOFS manually extracted currents and b) calculated current output from CANSARP Scientific for a simulation at (-47.829, 46.995) starting on August 4, 2007 for 48 hours. Note that north is up.* *57*

Figure 4.3 *Simulation of SLDMB 17316 on starting on August 4 at 0500Z for 96 hours at 6-hour intervals (displaying first 67 hours). The blue line represents the SLDMB Trajectory, the red line represents CANSARP Scientific's calculated trajectory and the grey quivers are CNOOFS current vectors..* *58*

Figure 4.4 *a) Mercator Currents and b) calculated current output from CANSARP Scientific for a simulation at (-47.829, 46.995) starting on August 4, 2007 for 48 hours. Note that north is up.* *59*

Figure 4.5 *Simulation of SLDMB 17316 on starting on August 4 at 0500Z for 96 hours at 6-hour intervals (displaying first 67 hours). The blue line represents the SLDMB Trajectory, the red line represents CANSARP Scientific's calculated trajectory and the grey quivers are Mercator current vectors.* *60*

Figure 4.6 *Mean position of 250 particles after 24 hours of drift with SLDMB 17316 using the Monte Carlo method for the a) CNOOFS and b) Mercator Currents.* *62*

Figure 4.7 *SLDMBs from August 2007 simulated with 24-hours of CNOOFS currents using the Monte Carlo Method with 250 particles.* *63*

Figure 4.8 *SLDMBs from August 2007 simulated with 24-hours of CNOOFS currents using the MiniMax Method. See Figure 2.5a for location with respect to bathymetry.* *64*

Figure 4.9 *SLDMBs from August 2007 simulated with 24-hours of Mercator currents using the Monte Carlo Method with 250 particles.* *65*

Figure 4.10 *SLDMBs from August 2007 simulated with 24-hours of Mercator currents using the MiniMax Method. See Figure 2.5a for location with respect to bathymetry.* *66*

Figure 5.1 *Search trajectories and velocity profiles using CNOOFS currents for SLDMB 17303, 17316, and 17347. Column 1: Drifter trajectory and CANSARP Scientific Search trajectory over 48 hours Column 2: Calculated velocity profile and CNOOFS current velocity profile comparison at start location of drift* *71*

Figure 5.2 *Velocity magnitude profile using CNOOFS data for a simulation at point (40, -65).* *73*

Figure 5.3 *Monte Carlo search areas with 1000 (green dashed line), 500 (red dashed line) and 250 (blue dashed line) particles after 24 hours for SLDMB 17303. Areas increase in size with the number of particles applied with values of 0.0183°², 0.0258°², and 0.0328°², respectively. The solid blue line is the SLDMB actual trajectory for 24 hours while the green dot represents the start of the drift and the red dot represents the end of the drift.* *78*

Figure 5.4 *Drift trajectory of lost mooring starting from 53° 10' N, 50° 54' W at 18:00Z on May 17, 2008. Reported locations illustrated from ARGO satellite fixes* *80*

Figure 5.5 *Predicted trajectory of mooring from 18:12 on May 17, 2008 for 94.3 hours using CNOOFS currents at 10 m depth. Actual drift trajectory is in blue with start location at location at 94.3 hours noted. Search trajectory and area are plotted in black. Bathymetry is contoured by multi-colored lines and labeled according to their depth in meters.* *81*

Figure 5.6 *CANSARP Scientific simulation on May 17, 2008 for 94.3 hours starting at 18:12:00 UTC run with CNOOFS currents with surface velocity field as quivers from AVISO altimetry data. Contours represent mean sea surface height in cm. Quivers represent sea surface velocity for the 17th of May. Black trajectory is the predicted drift trajectory by CANSARP Scientific and the circle is the proposed search area.* *83*

Figure 5.7 *Daily progression of mooring trajectory (black) with corresponding daily averaged sea surface height altimetry data on (L-R): a) May 17 , b) May 18, c) May 19, d) May 20, e) May 21. Drift trajectories are plotted from May 17 to end of day altimetry is plotted. The green dot indicates the mooring start location and the red dot indicates its last position on each day. Value of sea surface height is indicated on colored contours in units of cm* *85*

Figure 5.8 *Displacement calculations in the x and y directions where the current velocity is projected parallel and perpendicular to the local current in the region over a 48 hour period. Each of the 12 drifters explored are indicated by a different color dot in the plot. The mean displacement on this plot is (656.6991, 74.4230).* 88

Figure 5.9 *Normalized error calculations in the x and y directions where the current velocity is projected parallel and perpendicular to the local current in the region over 48 hours. Each color dot represents the error produced by a different drifter. The mean error position is (-0.273, 1.52)* 89

Figure B-1 *Time improvements made in Mercator Monte Carlo script by number of hours of simulation run and number of particles used.* B-2

Figure C-1 *Regular Mercator grid and irregular CNOOFS grid.* C-1

List of Abbreviations and Symbols

AOML: Atlantic Oceanographic and Meteorological Laboratory

ASW: Average Surface Wind

ASWORG: Antisubmarine Warfare Operations Research Group

BIO: Bedford Institute of Oceanography

CANSARP: CANadian Search and Rescue Planning

CASP: Computer Assisted Search Planning

CCG: Canadian Coast Guard

CCGC: Canadian Coast Guard College

CJMTK: Commercial Joint Mapping Tool Kit

CLIVAR: CLImate VARiability

CMC: Canadian Meteorological Center

CNOOFS: Canada-Newfoundland Operational Ocean Forecasting System

CSPM: Classical Search Planning Method

D_e: Total Drift Error

DAC: Data Assembly Centre

DFO: Department of Fisheries and Oceans

E: Total Error

EDS: Environmental Data Server

F: The Coriolis Parameter

ftp: File Transfer Protocol

GDP:	Global Drifter Program
GEM:	Generalized Equation-of-State Model
GPS:	Global Positioning System
GRIB:	GRIdded Binary
GTS:	Global Telecommunications System
GUI:	Graphical User Interface
IML:	Institute Maurice Lamontagne
ISDM:	Integrated Science Data Management
JRCC:	Joint Rescue Coordination Center
LIM:	Louvain-la-Neuve Sea Ice Model
LKP:	Last Known Position
LUT:	Local User Terminal
LW:	Leeway
MATLAB:	MATrix LABoratory
MEDS:	Marine Environmental Data Service
NEMO:	Nucleus for European Modelling of the Ocean
NetCDF:	Network Common Data Form
NOAA:	National Oceanic and Atmosphere Administration
NSAR:	National Search and Rescue
P & S:	Pressure and Sensor
PIW:	Person in Water
POC:	Probability of Containment
POD:	Probability of Detection

POM: Princeton Ocean Model

POS: Probability of Success

RCC: Rescue Coordination Center

SAR: Search and Rescue

SAROPS: Search and Rescue Optimal Planning System

SARP: Search and Rescue Program

SLDMB: Self-Locating Datum Marker Buoy

SSPM: Simplified Search Planning Method

SVP: Surface Velocity Program

TWC: Total Water Current

USCG: United States Coast Guard

U_{10}: Wind speed at 10m height above sea level

WCRP: World Climate Research Programme

WOCE: World Ocean Circulation Experiment

Chapter 1 Introduction

1.1 *An Overview of Search and Rescue*

Search and Rescue is used all over the world to locate missing people and objects, or to assist those in danger on both land and water. The focus of this thesis is ocean drift calculations applied in maritime Search and Rescue. In all Search and Rescue cases, notification or a distress signal must be received by the Search and Rescue coordination centre in order to begin the process of creating a search plan. This notification may come from the persons or vessel at risk, an observing vessel, or from individuals awaiting an overdue person/vessel. Once this notification is confirmed, a coordination centre begins creating a search plan using the most up-to-date and accurate information known about the case. Important information includes the Last Known Position (LKP) of the object, how long the object has been missing, and an accurate description of the object of interest, called the search object. These inputs are used, along with the corresponding environmental inputs (winds, currents, etc.) for the search, to run a computer program that applies search theory algorithms to help locate the search object. Each country has its own computer system that applies different calculations to predict the search object's drift in the ocean, but all aim to find the object in a reasonable period of time.

Once the search plan is prepared, Search and Rescue Units (vessels reserved specifically for finding search objects) are deployed. The type and number are dependent on the location of the search, and the vehicles available in the region. Fixed-wing aircraft, helicopters, and seagoing vessels may be deployed for the search. Each of these vehicles are requested to search a given area using a prescribed pattern from the search plan. It is the Search and Rescue Coordinator's job to provide the most efficient pattern based on the available resources and the area to be searched.

In addition to these Search and Rescue Units, any vessel in the area may be requested to assist with the search. These craft may be asked for information regarding the incident or may be requested to assist in the actual search process, depending on a number of circumstances. In Canada, requests from Canadian Coast Guard regarding search and rescue must be obeyed.

Once the search plan has been carried out, and every reasonable effort has been made to find the search object and the search is not successful, a call must be made as to when to reduce or terminate the search. This is done based on the environmental conditions in the area, available resources, and time lapsed. Each country has regulations governing this procedure.

While every country has variations in procedures and guidelines, the above is a general Search and Rescue process. Details and comparisons of each nation's methodologies follow.

1.2 *Background on the Canadian Coast Guard Search and Rescue Planning Program (CANSARP) Software*

The Canadian Coast Guard is currently using search planning methods developed for use in WWII. The original search theory's purpose was to determine an area in which to search for enemy vessels. Following the war, the United States Coast Guard took ownership of the algorithm and adapted it such that it was useful in Search and Rescue operations.

In the Simplified Search Planning Method (SSPM) – the manual method of plotting a search – a number of assumptions are made about the search object's probable location, the nature of visual detection, and the way in which searches are conducted. These include:

1) The possible search object locations are distributed around a datum position in a circular normal probability distribution
2) The means of detection are visual
3) The inverse cube model of visual detection[1] is sufficiently accurate under all search conditions
4) Searches are performed as series of equally spaced parallel sweeps relative to the search object
5) Specific levels of coverage (search effort) are used for each case in a series of searches for an object of interest

Currently, the Canadian Coast Guard employs the CANSARP software to automate the approach to searching. This automated approach allows the incorporation of more data, and more complex inputs to generate search scenarios in little time. The search planner is able to evaluate several possibilities using various times, positions, search object, situations, and environmental factors.

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[1] Inverse Cube Model: "The instantaneous probability that the search object will be detected is inversely proportional to the cube of the range from the observer of the object (Soza and Company, 1996)."

1.3 *Inputs for Search and Rescue Planning*

1.3.1 Last Known Position

CANSARP requires several factors in order to produce a search area, the most vital of these being the Last Known Position (LKP). This position is used to compute a datum (the most probable area of a search object corrected for drift over time, that increases with subsequent searches). Four possible scenarios generally exist for determining the LKP (CCG/DFO, 2000):

1) *Single Position Known*: The last observed position of the search object is of high certainty and reported by the vessel in distress or a witnessing vessel.
2) *Multiple Positions Known*: This situation involves the reporting of more than one location such that the actual last known position of the object is questionable.
3) *Track Known*: Here an intended search track is available, and possible locations along the track have been reported, but certainty may still be questionable.
4) *General Area Known*: If nothing more than a general region is known for the search object, then a search area is established based on fuel endurance of the search rescue unit, natural boundaries, and a suspected route.

1.3.2 Leeway

Movement of the search object through water, caused by the direct action of the wind on the exposed surfaces of the object is called Leeway (LW). The shape, size and orientation of the search object cause the LW term to vary making it difficult to determine impact on object direction and speed (CCG/DFO, 2000). Leeway is applied downwind if no divergence (possibility of more than one direction of drift due to type/orientation of drift object in the wind) exists, and is applied to the left and right of the downwind direction, should the object diverge. Leeway is applied to the search object in a series of steps as follows (CCG/DFO, 2000):

1) Determine average surface wind (ASW) for drift interval
2) Determine the search object
3) Use leeway rates tables from National SAR manual and extract appropriate information and plug into formula:

$$LW\,Rate = U_{10} \times coefficient + correction \tag{1.1}$$

where U_{10} is the wind speed at 10 m height above sea level.

4) Multiply ASW by the extracted formula to determine LW rate
5) Multiply LW rate by the drift interval to get LW vector length

And then direction is determined:

6) a) If there is no divergence, the direction is directly downwind.

b) Otherwise, the reciprocal (180° difference) of the wind direction is taken, and the divergence angle as per the National SAR manual is both added and subtracted to the downwind direction to produce the minimum and maximum expected divergence.

Leeway rates and directions are implemented from tables in the National SAR Manual Chapter 7, Section 7.31, that were developed through observations of common drift objects and can be used to calculate leeway speed and divergence for various objects at wind speeds of 5 to 40 knots using wind spends measured at the 10 m standard reference height (Allen & Plourde, 1999).

1.3.3 Ocean Currents in CANSARP

The final product that CANSARP uses is the total water current (TWC) to indicate the datum point from which the search will be based. This current is defined as the vectorial sum of all applicable currents (sea current or climatological current, tidal current, wind driven current, etc) in a particular drift plot (CCG/DFO, 2000). In CANSARP Scientific (a controlled implementation of CANSARP for testing purposes discussed in greater detail in Section 1.6), the total water current is computed based on whether ocean model currents are applied. If model currents are used, all current and wind forces are considered a part of the current field and no calculation is required. If simple measurements of current speed are applied, then winds and any other suspected current forces must be vectorially summed to produce the total water current vector.

There is an order by which currents are applied in the Canadian Coast Guard's version of CANSARP. Of first priority is the measured (observed) current, followed by Self Locating Datum Marker Buoy (SLDMB) data, then 2 model output currents; the Grand Banks Model and the Institute Maurice Lamontagne (IML) Gulf Model, followed by subjective currents, wind driven currents, tidal currents, and finally sea currents (Canadian Coast Guard College [CCGC], 2005). The first three current types are preemptive in CANSARP such that just one of the selections are used (in the order listed) regardless of how many other current types are selected (no calculation of total water current required) while the final four current types can be vectorially added (CCGC, 2005).

1.3.4 Observed (Measured) Currents

In situ observed currents are estimated from surface drifters released by the on-scene search and rescue unit. These currents are important to a search since they are measured in the region of search where information is required (CCGC, 2005). An aircraft or ocean vessel deploys a surface buoy into the water at the Search and Rescue Scene nearest the last known position of the search object as possible. Location data is collected by the drifter's internal GPS and is transferred via ARGOS satellite to the LUT (local computing station receiving transmitted data) for transfer to one of the three Canadian Coast Guard's Joint Rescue Coordination Centre (JRCC) and then to the CANSARP computing stations for SAR use (Figure 1.1).

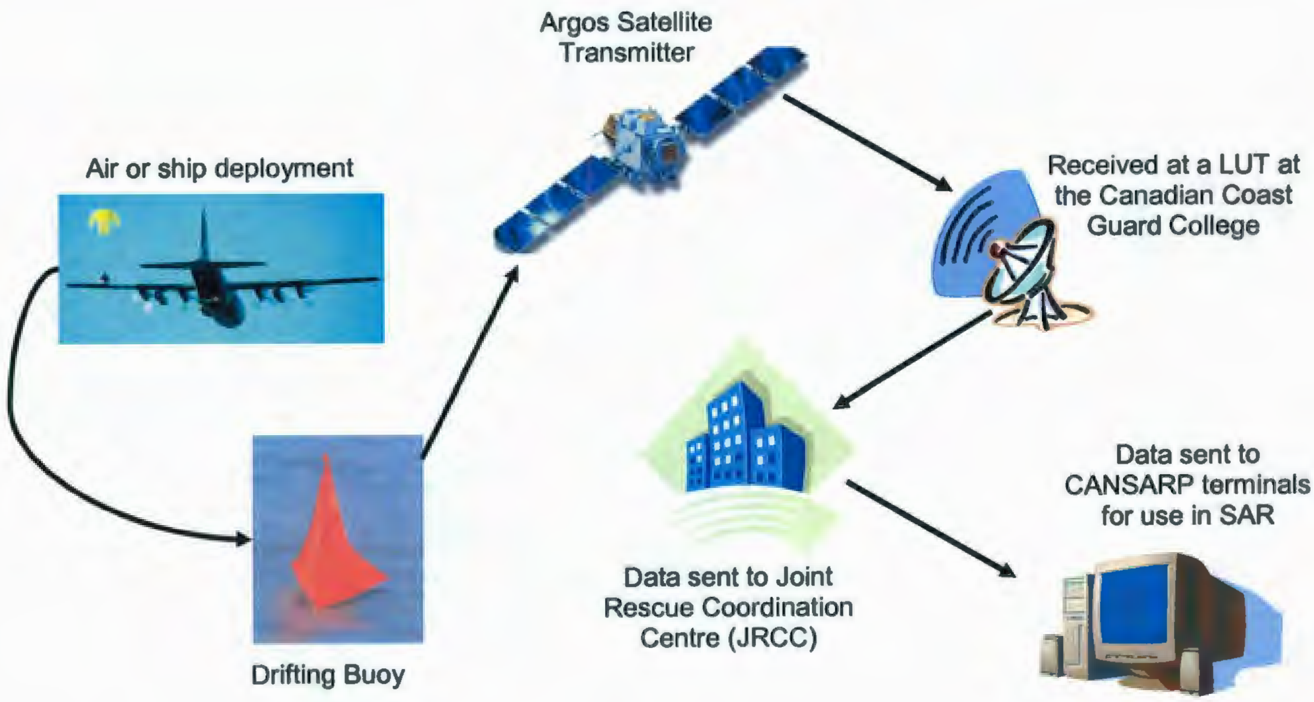

Figure 1.1 *Sample data transfer from a drifting buoy to CANSARP from deployment to the point that it is usable in CANSARP for search planning.*

1.3.5 Ocean Forecast Models

Presently, CANSARP uses ocean forecast systems from the Grand Banks and IML models that take real time data and project currents for hours to days in advance (CCGC, 2005). The data is automatically downloaded to the CANSARP workstation for predicting drift (CCGC, 2005). Each of these models has different boundaries. The IML model encompasses the St. Lawrence River, the Gulf of St. Lawrence, and the southwest coast of Newfoundland and Labrador/the northeast coast of Nova Scotia (Saucier et al., 2003), as in Figure 1.2 (a). The Grand Banks model has boundaries encompassing the entire Labrador Sea as per Figure 1.2 (b) (Tang et al., 2008).

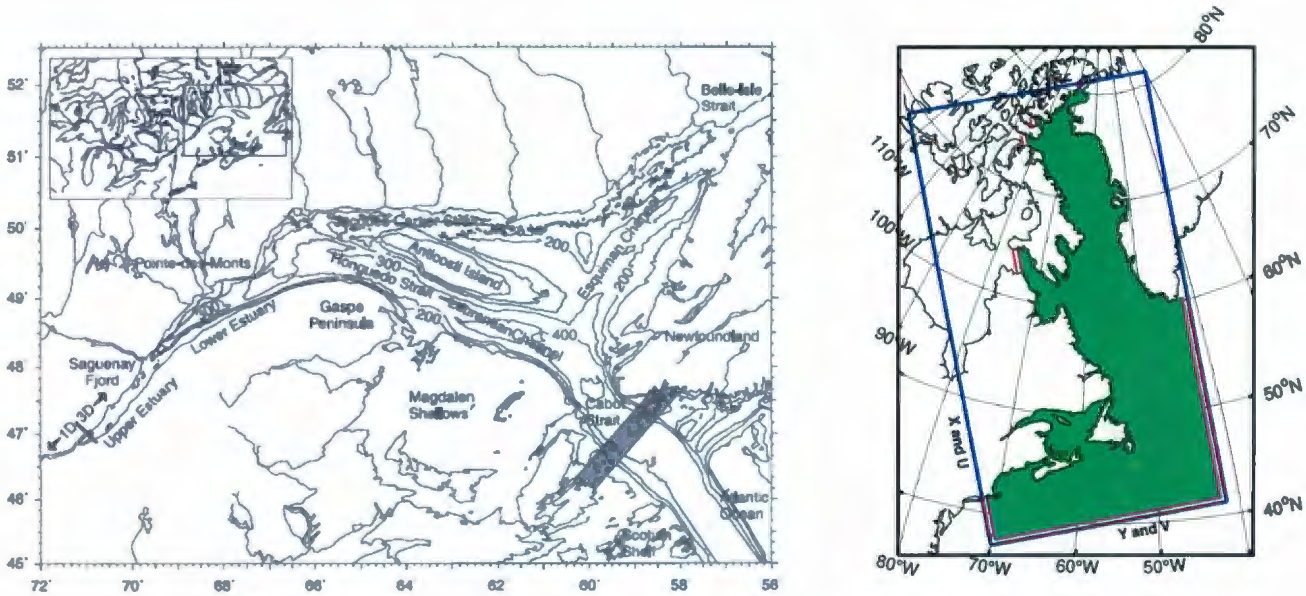

Figure 1.2 *Delineations of model boundaries used in CANSARP*
a) Bathymetry of the Gulf of Saint Lawrence and a subset of the IML Model Boundaries in upper left panel.
b) The Grand Banks model geographical boundries delineated by the blue line.

The IML model has a horizontal resolution of 5 km, and a vertical resolution of 5 m from the surface to 300 m depth. Below 300 m, the resolution is at 10 m increments (Saucier et al., 2003). This model is hydrostatic and provides solutions to the mass, momentum, heat, and salinity conservation equations. Details and equations can be found in Saucier et al. (2003).

The Grand Banks model is based on the Princeton Ocean Model (POM). It has a free surface and applies sigma coordinates in the vertical direction. The model determines velocity, potential temperature, salinity, and turbulence. The model grid is of 1/6° × 1/6°, and has 16 sigma levels in the vertical. Yao & Peterson (2000) discusses this model in great detail.

1.3.6 Subjective Currents

Subjective currents are estimated from the SAR scene or from other data sources and can be combined vectorially with other current sources to produce a resultant current (CCGC, 2005). They differ from measured currents as they are estimated from the scene or from other data sources.

1.3.7 Wind Currents

CANSARP calculated wind currents are local currents generated by the effect of wind on surface water calculated by CANSARP using observed and forecast data, and should be used in conjunction with tidal currents and sea currents, if available (CCGC, 2005).

There are two types of calculations for wind driven currents presently used in CANSARP; the empirical or Rule of Thumb method and the Ekman method. The Empirical method uses 3.3% of the wind speed offset 20° to the right of the wind direction (CCGC, 2005). The Ekman method is based on the Ekman boundary theory (Madsen, 1977) and is generally used when time permits as it is computationally more demanding (CCGC, 2005).

1.3.8 Tidal Currents

Tidal currents are only available for select geographical regions in CANSARP. These currents are static models that do not incorporate external inputs, but do change in time, and are calculated in 15-minute time steps (CCGC, 2005). These currents account for the effect of tides on currents in the ocean.

1.3.9 Sea Current

The last type of current is the sea current. In CANSARP, "sea currents" refer to steady state ocean currents such as climatology, but these change seasonally. One-hour time steps are used in CANSARP to calculate sea current drifts (CCGC, 2005).

1.4 *Search Planning Summary*

There are five basic steps involved in search planning in Canada (CCG/DFO, 2000):

1) Estimating the datum (most probable position of a search object corrected for drift over time) for an appropriate search start time
2) Determining a search area surrounding the datum(s) considering the probable drift and navigation errors
3) Selecting the appropriate search pattern considering the size of the area and capabilities of the resources
4) Determining the area of coverage considering factors affecting the probability of detection, track spacing, and number of resources; and
5) Developing an optimum and attainable plan

1.5 *United States Coast Guard (USCG) Model*

The United States Coast Guard's search model has origins dating back to 1942 when the US Navy's Antisubmarine Warfare Operations Research Group (ASWORG) responded to a German submarine threat in the Atlantic (Frost & Stone, 2001). Bernard Koopman, who joined ASWORG in 1943, has been credited with the statistical foundation of the search theory (Frost & Stone, 2001). Koopman defined the elements of an optimal search as having the following four properties (Frost & Stone, 2001):

1) A prior probability density distribution on search object location
2) A detection function relating search effort density and the probability of detecting the object if it is within the searched area
3) Limited search effort
4) Maximizing probability of finding the object subject to effort constraint

The optimal search problem is defined as "finding the allocation over some subsets of the possibility area for the limited amount of available search effort that maximizes the probability of success." Solving this problem indicates how search effort should be distributed.

Koopman successfully developed visual, sonar, radar, and mathematical models for locating both stationary and moving targets, and document a few cases of successful search planning using his basic methods.

In the early 1960s the Americans tried out the MiniMax theory, similar to the one the Canadian Coast Guard uses today, which was intended to allow different drift scenarios and handle a maximum and minimum drift parameter calculation. Leeway was the most common of these drift parameters, and tables were created with leeway parameters for reference (Frost & Stone, 2001).

The Search and Rescue Program (SARP) that followed was the first attempt at computer based search plan approach around 1970 (Frost & Stone, 2001). It was essentially a computer-coded version of the Classical Search Planning Method (CSPM) with minor improvements to the environmental variables. It was designed with simplicity to the user in mind, requiring just 4 input variables; incident date and time, last known position of the distressed craft, probable position error of the distressed craft, and probable error of the search craft (Frost & Stone, 2001). SARP calculated drift trajectories based on hourly time steps, and accessed wind and current data using nearest-neighbor interpolation (Frost & Stone, 2001).

In years following, the Computer Assisted Search Planning (CASP) was implemented which supplemented the CSPM module by taking a computer simulation approach to search planning and evaluation (Frost & Stone, 2001). This was a semi-random approach using the Monte Carlo method, which will be discussed in greater detail in section 3.2. The CASP program applies 500 points centered on the "head" of the mean sea current vector using a stochastic approach to determine locations independent of one another, producing a region of normally distributed points (Frost & Stone, 2001). When error is summed to the mean sea current vector, the resultant vector is used to compute a sample drift velocity. This sample drift velocity is found by taking samples from the environmental forces (winds, currents, etc). The drift velocity is then multiplied by a time interval to obtain sample drift distance (Frost & Stone, 2001). This procedure repeated several times will provide a reasonable probability distribution for search. According to the number of replications requested, the search is then updated using the Monte Carlo approach. The solution does not resemble a circular pattern at all like the CSPM provided. Probability densities are represented by color in the CASP output (Frost & Stone, 2001).

By 2001, the United States Coast Guard was using more advanced techniques to determine the trajectories of oil spills than they were for people in distress, and the Search and Rescue Optimal Planning System (SAROPS) system came into development. The SAROPS 1.0 alpha version was released in March of 2005, with an operational version implemented in January of 2007 (Allen & Howlett, 2008).

SAROPS has three main components; ArcGIS/Commercial Joint Mapping Tool Kit (CJMTK)-based graphical user interface (GUI), Environmental Data Server (EDS), and simulator engine that performs the particle motion and search optimization (O'Donnell, J.D. et al., 2005). The GUI applies a wizard-based interface, supports vector or raster plots, displays environmental data, and displays recommended search patterns and probability maps (Spaulding, 2008). The EDS requires surface current and wind data, and any other available factors including visibility, cloud cover, sea state, etc. to run (Spaulding, 2008). It automatically selects the best data available to run, and accommodates for varying spatial data resolutions (Spaulding, 2008). Sources of this data are National Oceanic and Atmospheric Administration (NOAA), Navy, regional associations, universities and commercial providers. This data is passed to the simulator engine which computes the Monte Carlo particle simulation and simulates distress incidents and outcomes, post-distress motion, produces a near-optimal search plan, computes a cumulative probability of success, and accounts for previous unsuccessful searches when formulating subsequent searches (Spaulding, 2008).

There are identified needs and a plan for the development of open-sourced coding and more readily available versions of the software for the scientific community to review and use, as SAROPS is not currently a product available for public use (Allen & Howlett, 2008).

1.6 *Norwegian Search and Rescue Model*

The Norwegian model called LEEWAY also employs the Monte Carlo method. It is a part of a suite of oceanic models including a ship drift model and a 3-dimensional oil spill model. It was developed and implemented by the Norwegian Meteorological Institute for the operational community. The program has the following features:

1) It takes current vectors at 0.3 m to 1.0 m depth (Breivik, n.d.).
2) It incorporates the concept of slippage; the motion relative to the ambient current at a certain depth comparable to the draft of the object. In the absence of wind, slippage is zero (Breivik & Allen, 2008).

3) The search object of interest is assumed to adjust its motion instantaneously once the wind acts on it (Breivik & Allen, 2008).
4) Surface wind fields are developed from an operational 3-D baroclinic ocean model run by the Norwegian Meteorological Institute, and is a modified version of the Princeton Ocean Model (POM) which solves the primitive equations of motion by applying the Boussinesq and hydrostatic approximations, and accounts for conservation of heat and salt. It is driven by atmospheric forcing (Breivik & Allen, 2008).
5) Stokes drift is assumed in leeway drift (Breivik & Allen, 2008). That is, the motion of the drifting object moving in the direction of propagation of the waves (Kundu, 1990) is accounted for in the leeway term. There is no physical connection of Stokes' drift to winds in this case.

Using the above model, LEEWAY attempts to determine a Probability of Success as follows (Breivik & Allen, 2008):

$$POS = POC \times POD \tag{1.2}$$

where POC is the probability of containment, and POD is the probability of detection. A Monte Carlo approach was thus decided upon to produce a probability distribution for both the latitude and longitude uncertainty values. This is because Markov processes are of random evolution and are "memoryless" depending only on the current state, and not on how an object behaved in the past to arrive in the current state (Korn & Korn, 2000), and in the search model, concern is placed on the Last Known Position. Throughout the integration of the members involved in the Monte Carlo problem, once movement left or right of downwind has begun, the object cannot cross paths and change direction. In other words, no jibing is permitted.

The initial drift distribution for the Norwegian drift model is prescribed on the accuracy of the LKP. If the LKP is well known, the initial drifter locations in the ensemble are tightly concentrated. In LEEWAY, the ensemble size is set to 500 (see Breivik, 2008 for further detail). The search area is determined using the convex hull polygon derived from the particle distribution. The convex hull of a set of points where the smallest convex polygon that encompasses all points of the set (Brown, 1979). Figure 1.3 illustrates a convex hull surrounding 225 points with values between 2 and 8 in both the x and y axis.

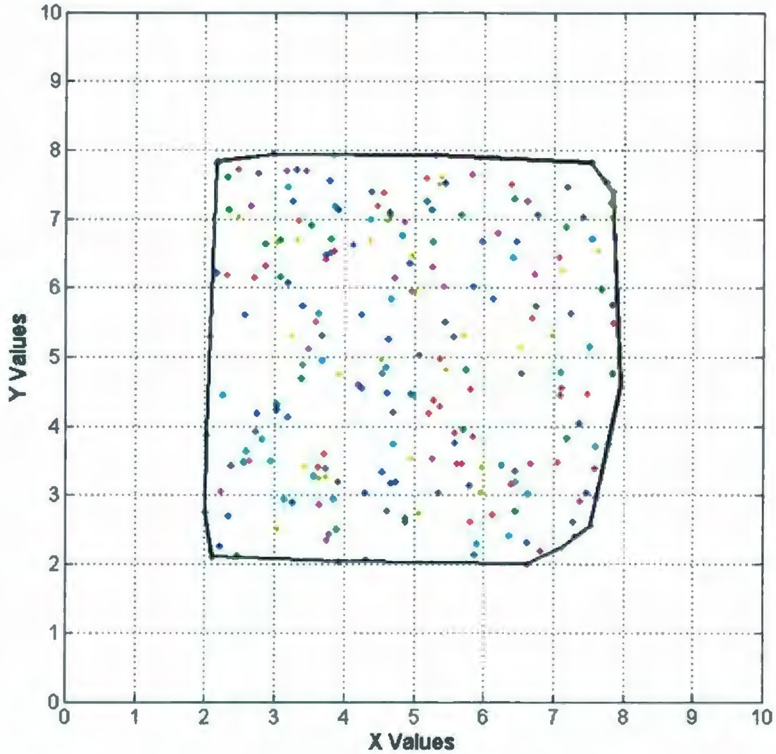

Figure 1.3 *Example of a convex hull plotted around points ranging between 2 and 8 in both the x and y axis. Note that the figure is formed by outlining the outermost points from the cluster of particles.*

It has been noted that validation of the Norwegian model is lacking. Small drift experiments have been undertaken, but no evaluation of the model has been formally completed. Of major concern in this method is the lack of account for jibbing, capsizing or swamping of the search object (Breivik & Allen, 2008). A further improvement suggested by Breivik (2008) is for a higher resolution model, particularly near shore where the vast majority of incidents take place would be an asset.

1.7 *Thesis Objective*

The Canadian Coast Guard (CCG) Search and Rescue (SAR) objective is to "prevent loss of life and injury through search and rescue alerting, responding, and aiding activities using public and private resources (CCG/DFO, 2000)." The purpose of this project is to validate and improve the Canadian Coast Guard Search and Rescue Planning program (CANSARP) used by the Rescue Coordinator at the Rescue Coordination Centre. The ultimate goal is to improve the efficiency of search theory given present day computing capacity and available environmental inputs in efforts to fulfill the CCG mandate.

This project addresses fine tuning search and rescue theory as well as numerical simulations to demonstrate the impact of applying updated search and rescue theory. Statistical success of the existing algorithm called "MiniMax" are determined and compared to the Norwegian SAR version of the Monte Carlo method. All computation was done in a MATLAB computing environment using a coded version of the CANSARP program called CANSARP Scientific. Using various sea and wind current inputs, the most effective combination of algorithms and inputs will be determined mathematically and proposed for eventual implementation into the CANSARP program.

Current inputs being used include historical seasonal currents, and outputs from the Canada-Newfoundland Operational Ocean Forecasting System (CNOOFS) and Mercator model forecasts, as discussed in sections 2.2 and 2.4. Wind inputs used in CANSARP Scientific can be manually input as constant values, although option exists to read the Canadian Meteorological Center's (CMC) Generalized Equation-of-State Model (GEM) winds in Gridded Binary (GRIB) format.

Chapter 2 Environmental Data Sets

Environmental data sets include current and wind data, as well as ground truth data. The currents used in Cansarp and Cansarp Scientific are either climatological currents or model output currents, and the winds are CMC Winds from Environment Canada. Ground truth data includes a variety of drifting buoys that simulate drifting objects in SAR cases.

2.1 *Climatological Currents*

Climatological Currents are a collection of averaged current velocities for 2 seasons; winter and summer. The sources of these currents include geostrophic calculations in the Gulf of St. Lawrence over a 19-year period, a 38-year gridded surface current map of the Atlantic Ocean by the International Ice Patrol, and a collection of American and British pilot charts of the North Atlantic Ocean combined with gridded data from CANSARP V2.0 (Seaconsult Marine Research Ltd., 1993; Murphy & Hanson, 1989; El-Sabh, 1976). The coverage of these current grids is limited to the Northwest Atlantic Ocean as seen in Figure 2.1, and the use of these currents for Search and Rescue has some obvious limitations. Due to geographical and temporal resolution, these currents are applied in the original CANSARP program only when no other data is available for a particular case, or when little is known about the conditions at the drift target's LKP.

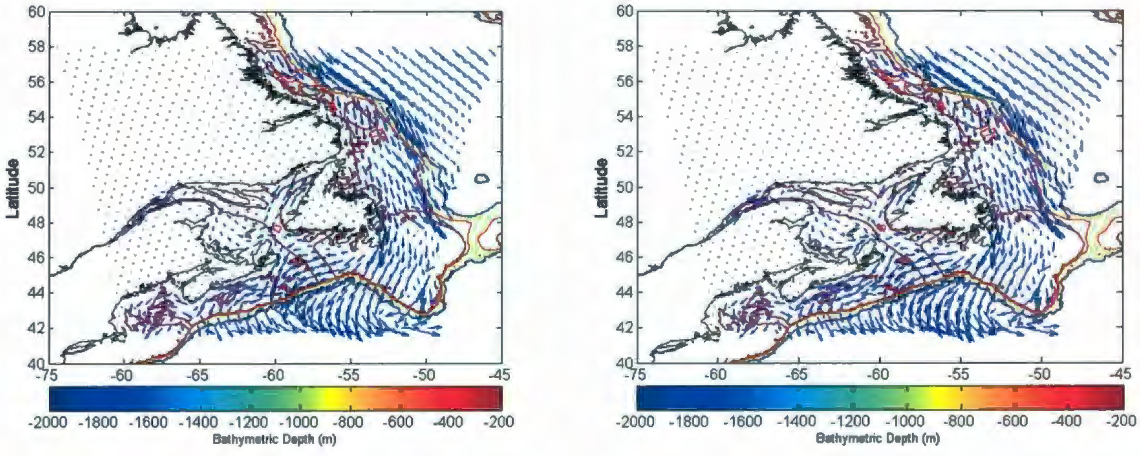

Figure 2.1 *Climatological sea currents for a) Summer and b) Winter as used in CANSARP Scientific. Coastline and bathymetry displayed to provide reference. Quivers shown are reduced such that 1/9 of all quivers on grid are displayed.*

2.2 *Mercator Currents*

Current files obtained from the French operational ocean forecasting organization, Mercator-Ocean (www.mercator-ocean.fr), were available for CANSARP Scientific simulations. The Mercator-Ocean Forecasting system is based on the NEMO ocean model, forced by atmospheric wind stress, evaporation, precipitation, sensible heat flux, latent heat flux, infrared flux, cloud coverage, surface humidity, air temperature at 2 m, and winds at 10 m (Modeling the Ocean at Mercator, 2007) . The Mercator system features data assimilation of satellite and in-situ data.

This data has been used in three different formats:

Table 1 Available Configurations of Output Data from Mercator Model

Data Type	Horizontal Resolution (°)	Vertical Levels	Global Coverage
PSY3V1R1	1/4	46	Global
PSY3V2R2	1/4	50	Global
PSY2V2R1	1/15	43	North Atlantic and Mediterranean Sea

Each of these data sets provides daily outputs of a number of state variables, sea ice variables, atmospheric forcing, and diagnostic variables. Of use in CANSARP Scientific are sea current velocity readings from the output state variables.

2.3 *CNOOFS Currents*

The Canada-Newfoundland Operational Ocean Forecasting System (CNOOFS) is a quasi-operational system under development for providing regional ocean information for applications like search and rescue, navigation through ice, the offshore oil industry, weather forecasts, and marine habitat management in the Northwest Atlantic Ocean. Its goal is to provide a coupled ice ocean forecasting system enabling users to make better at-sea decisions (CANADA-NEWFOUNDLAND OPERATIONAL OCEAN FORECASTING SYSTEM [CNOOFS], 2007).

The CNOOFS model produces a daily forecast using the Nucleus for European Modeling of the Ocean (NEMO) to determine the ocean state (CNOOFS, 2007). It applies 1-way nesting within a Global Ocean Forecast System (Mercator's PSY3V2 currents with global, native grid at 1/4° horizontal resolution and 43 vertical levels) and Environment Canada's GEM winds forcing at 33 km resolution to predict the 3-D temperature, salinity, and ocean currents at hourly intervals (CNOOFS, 2007). Its domain ranges 103.12 W to 27.23 W longitude and 26.69 N to 83.68 N latitude with closed boundary conditions on the eastern and southern boundaries (CNOOFS, 2007). At present, this model applies the free-surface and uses tidal forcing with one main component and outputs at 1/4° in the horizontal and 46 levels in the vertical (CNOOFS, 2007).

2.4 *Canadian Meteorological Centre Forecast Winds*

The Environment Canada Canadian Meteorological Centre (CMC) Forecast Winds in the GRIB (GRIdded Binary) format are available from two different forecast systems; a GEM regional and a GEM global format available in both low and high spatial resolution files that provide a forecast for twice a day; 0Z and 12Z.

The low resolution files in regional model output offers 0 – 48 hour forecasts with surface fields available at 3-hour intervals (Environment Canada, 2007). At 60°N, the resolution is 60 km. The lower resolution global model output offers 0 – 120 hour forecasts at 6-hour intervals with 2.0° degree resolution (Environment Canada, 2007).

The high resolution files are global at 0.6 x 0.6° and 30 km resolution, while the regional files are at 15 km resolution (hour forecasts at 6-hour intervals with 2.0° degree resolution (Environment Canada, 2007). Again the regional forecasts are 0-48 hours while the global forecasts offer 0 – 144 hours (hour forecasts at 6-hour intervals with 2.0° degree resolution (Environment Canada, 2007). The time resolution of the files is 3-hourly or 1-hourly depending on files selected.

In CANSARP Scientific, it is possible to apply any of the above formats, but most commonly used are high resolution files at 1-hourly resolution in efforts to provide the highest definition possible for a given simulation. At present, the official CANSARP program does read GRIB winds in a similar manner, but reads lower resolution winds at 6-hourly synoptic intervals for a preferred 48-hour period.

Based on the date of the simulation in CANSARP Scientific, the system is programmed to select the best available GRIB wind file for the scenario. Selection is based on a pivot date of April 4, 2005. Simulations for dates prior to the pivot date use the regional 3-hourly winds whereas those following the pivot date apply the regional 1-hourly winds. This can be varied based on available data.

The CANSARP program downloads environmental inputs twice daily from the IML and Grand Banks Ocean Model as well as the CMC winds. IML Gulf data is downloaded once a day from the server at IML in Rimouski, Quebec. The current data output from the Grand Banks model is updated twice daily by the Bedford Institute of Oceanography and passed to a server at the Canadian Coast Guard College for implementation into CANSARP. The CMC winds are downloaded hourly (the wind data includes hourly wind observations in addition to the GEM model output, unlike CANSARP Scientific) from a server at the Canada Ice Center though the data is produced by the group at CMC in Dorval. All environmental data is obtained at 1 hour resolution or is interpolated to one hour resolution.

GRIB is a standard compact data format for gridded meteorological data. GRIB Edition 2 is the current standard (Environment Canada, 2007).

2.5 *Self-Locating Datum Marker Buoys (SLDMBs)*

Self-Locating Datum Marker Buoys (SLDMBs) determine and transmit their own position via satellite transmission (CCG/DFO, 2000). They are used to determine the environmental effects (currents, winds, etc) on drifting objects, and to track debris of a SAR incident in the water during a search procedure, in efforts to reduce the size of the overall search area. A Canadian company, Seimac, fabricates SLDMBs composed of an air deployable buoy, GPS positioning system, an ARGOS satellite transmission system, and a sea surface temperature sensor. They can be set-up to simulate either a person in water (PIW) or a 4-person liferaft, and have a lifespan of about 5 days once deployed.

The data transmitted from the SLMDBs are received by the Rescue Coordination Centre (RCC) that deployed the drifter in a SAR case, or in many cases, by a research agency Local User Terminal (LUT), for analysis and testing. This project uses SLDMB track data from the Canadian Coast Guard College archival ftp site: ftp://loki.cgc.gc.ca/data/argos/archive.

Figure 2.2 *The air or sea deployable Self Locating Datum Marker Buoy (SLDMB) is composed of an air-deployable buoy, a GPS receiver, and an ARGOS satellite data transmitter (http://www.seimac.com/).*

2.6 *World Ocean Circulation Experiment (WOCE) Drifters*

In addition to the SLDMB drifters, WOCE drifters were used in this project for both validation and experimental purposes. While these drifters serve a similar purpose to the SLDMBs, they have slightly different characteristics and were created for different reasons.

The World Ocean Circulation Experiment (WOCE) was a large experiment under the World Climate Research Programme (WCRP). As part of the goal to observe poorly understood oceanographic processes a drifter program was delivered. The WOCE projects continued partly post 2002 through the CLImate VARiability program (CLIVAR). Drifters in the WOCE program provided validation data. They are usually drogued at 10 or 15 m and transmit their positions via the ARGOS satellite transmission system.

Drifting buoys provide information about surface drift which can be used to compare to models and satellite data, and can contribute to circulation models. The Marine Environmental Data Service (MEDS) in Canada is part of the Surface Velocity Program Data Assembly Centre (DAC) that combined with the United States' Atlantic Atmospheric and Oceanographic Laboratory, assembled and made data from WOCE drifters of satisfactory quality available to the public. Data interpolated to 6-hourly intervals is available through this program (Department of Fisheries and Oceans Canada [DFO], 2007).

The MEDS database is a part of the Integrated Science Data Management (ISDM) branch of the Department of Fisheries and Oceans (DFO) Canada. ISDM receives, processes, filters, and archives drifting buoy data over the Global Telecommunications System (GTS) and also archives non-real time data from other sources. This data is attainable by making a formal request to the DFO with the specifics of data required. This data includes more than 22 million drifter position records of GTS data from 1978 onward, and Global Drifter Program (GDP)/ formerly Surface Velocity Program (SVP) WOCE data available from 1979 to present with drogued buoys available up to just 2003 (DFO, 2007). The Raw and Pressure and Sensor (P & S) data come from the Atlantic Oceanographic and Meteorological Laboratory (AOML), also under the GDP. The Raw files are data received by the AOML that are placed in an archive. The P & S files are merged pressure and sensor files containing edited pressure data with buoy ID, date time and position and sensor output data containing buoy ID, date time and sensor values of temperature and sometimes salinity.

2.7 *Drifter Use*

In the case of CANSARP Scientific, these drifters are used as search targets. They are input according to their identification number and simulations are run based on their LKP position and time. Simulations can be run based on whether the drifter is drogued, representing either a person in the water (PIW) of a liferaft.

In an effort to determine the best dataset for use with CANSARP Scientific, a cumulative list of drifter sources was composed.

Table 2 Drifter Data and Sources with Contact Names

Data Set	Contact	Location
SLDMB	Ron Dawson/Peter Smith Canadian Coast Guard College Ron.Dawson@dfo-mpo.gc.ca Peter.Smith@dfo-mpo.gc.ca	ftp://loki.cgc.gc.ca/data/argos/archive
MEDS GTS	Luc Bujold Integrated Science Data Management Department of Fisheries and Oceans Canada Luc.Bujold@dfo-mpo.gc.ca	http://www.meds-sdmm.dfo-mpo.gc.ca/meds/Databases/DRIBU/drifting_buoys_e.htm *via* http://www.meds-sdmm.dfo-mpo.gc.ca/meds/Contact_US/Request_e.asp
MEDS P & S	Downloaded from Site No Contact	http://www.meds-sdmm.dfo-mpo.gc.ca/meds/Prog_Int/CLIVAR/SVP/kiel/Data_e.asp
MEDS Raw	Downloaded from Site No Contact	http://www.meds-sdmm.dfo-mpo.gc.ca/meds/Prog_Int/CLIVAR/SVP/kiel/Data_e.asp
Davis Floats	Arthur Allen United States Coast Guard Arthur.A.Allen@uscg.mil	ftp://www.rdc.uscg.gov/sldmb.zip
F156	Mary Hollinger National Oceanic and Atmospheric Administration Mary.B.Hollinger@noaa.gov	Obtained from a temporary ftp site
IIP	Donald Murphy International Ice Patrol Donald.L.Murphy@usgc.mil	Attached via e-mail as per July 23, 2007

Of the above drifter data, the SLDMBs and MEDS drifters are used here since SLDMB data is currently used by the Coast Guard for marking and studying SAR cases and the MEDS dataset is comprehensive and vast with both drogued and undrogued cases. The total number of drifters from 1995 to 2007 in the Northwest Atlantic is seen in Figure 2.3:

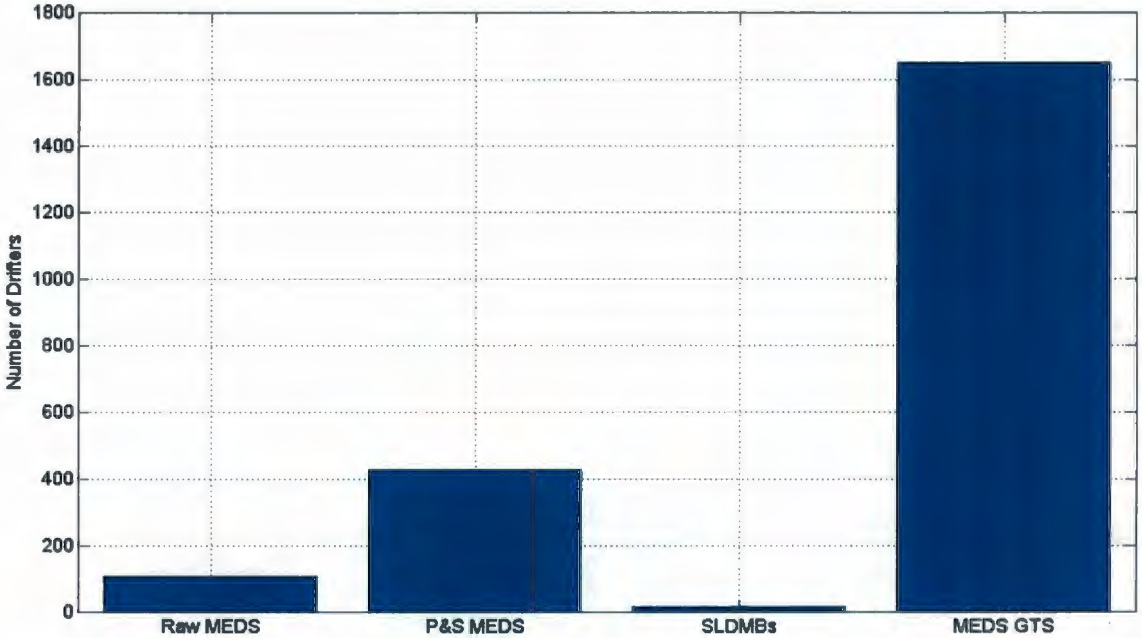

Figure 2.3 *Comparison of amount of available drifter data between -90° and -30° west, 25° and 80° north. From this plot it is apparent that the GTS data from MEDS has a vast supply of drifters, while the SLDMBs are lacking.*

As per Figure 2.3, the MEDS Global Telecommunications System (GTS) data contains approximately 4 times more drifter position data as MEDS Pressure and Sensor (P & S). It is also quite evident that the SLDMB data contains very few drifters, which is unfortunate as this dataset is important to this project.

Each of the data sets had a different range of availability; GTS runs from 1978 to present, P & S runs from 1989 to 2006, Raw runs from 1993 to 2003, and SLDMBs from 1997 to 2007. There is also a kriged[2] data set available from 1989 to 2006 though it was not explored as interpolated data is not of as much interest for this project. From each of the above sets, several years of data were obtained for exploration according to

[2] Kriging is a geostatistical optimal interpolation technique used to interpolate unknown values at known locations by applying a semivariogram. It incorporates measures of uncertainty and error, and optimal weighting can be applied based on the semivariogram used (Cressie, 1990).

availability and size of files at the time of download. Figure 2.3 below illustrates the datasets obtained for this project. A useful period of time for analysis, largely dependent upon environmental inputs, was selected for more consistency, once data analysis began.

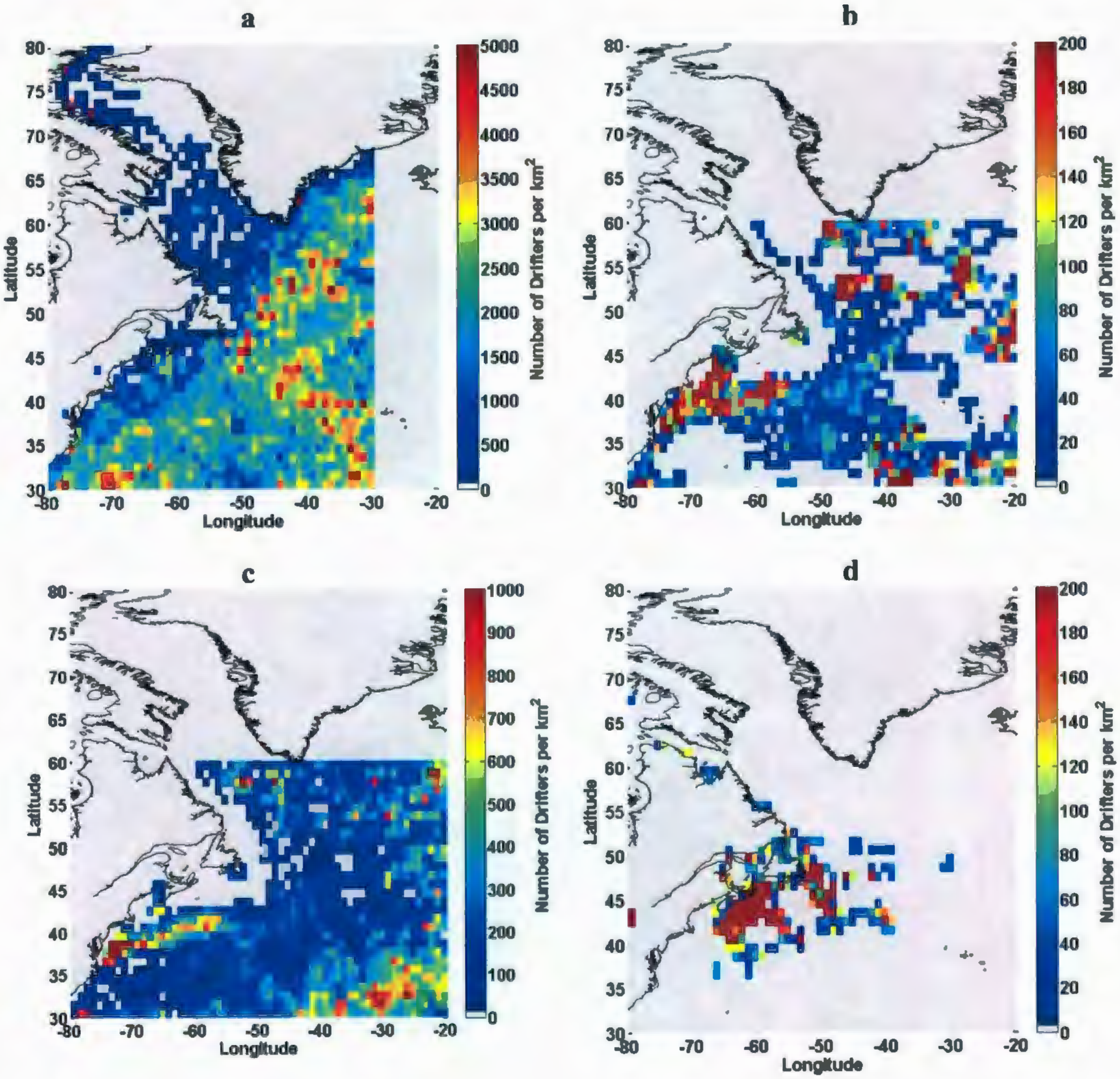

Figure 2.4 *Number of observed drifter data per squared kilometer for available timeframes for: a) MEDS GTS 2001-2007 b) MEDS Raw 1994-2002 c) MEDS P&S 1989-2003 and d) SLDMBs 1999-2007. Note varying density scales for plots.*

One possible solution to the inconsistent time and shortage of SLDMB data issues would have been to obtain older data (pre 1998), but corresponding environmental inputs for earlier dates was difficult to obtain. The focus in this thesis will thus be on 12 SLDMB drifters from August 2007 that were released on the Newfoundland shelf. This was decided because the most up-to-date model data was available for use in this period, and because there were enough drifters in our region of peak interest. Findings in this area would be expanded and tested with various other drifters in locations off the shelf following primary analysis. Figure 2.5a shows the available SLDMB drifters from the August 2007 dataset, while Figure 2.5b illustrates the available MEDS GTS drifters for the same month. Figure 2.6 compares the velocities at which the SLDMBs and MEDS GTS drifters travel. Their mean velocities indicate that their drift characteristics are similar.

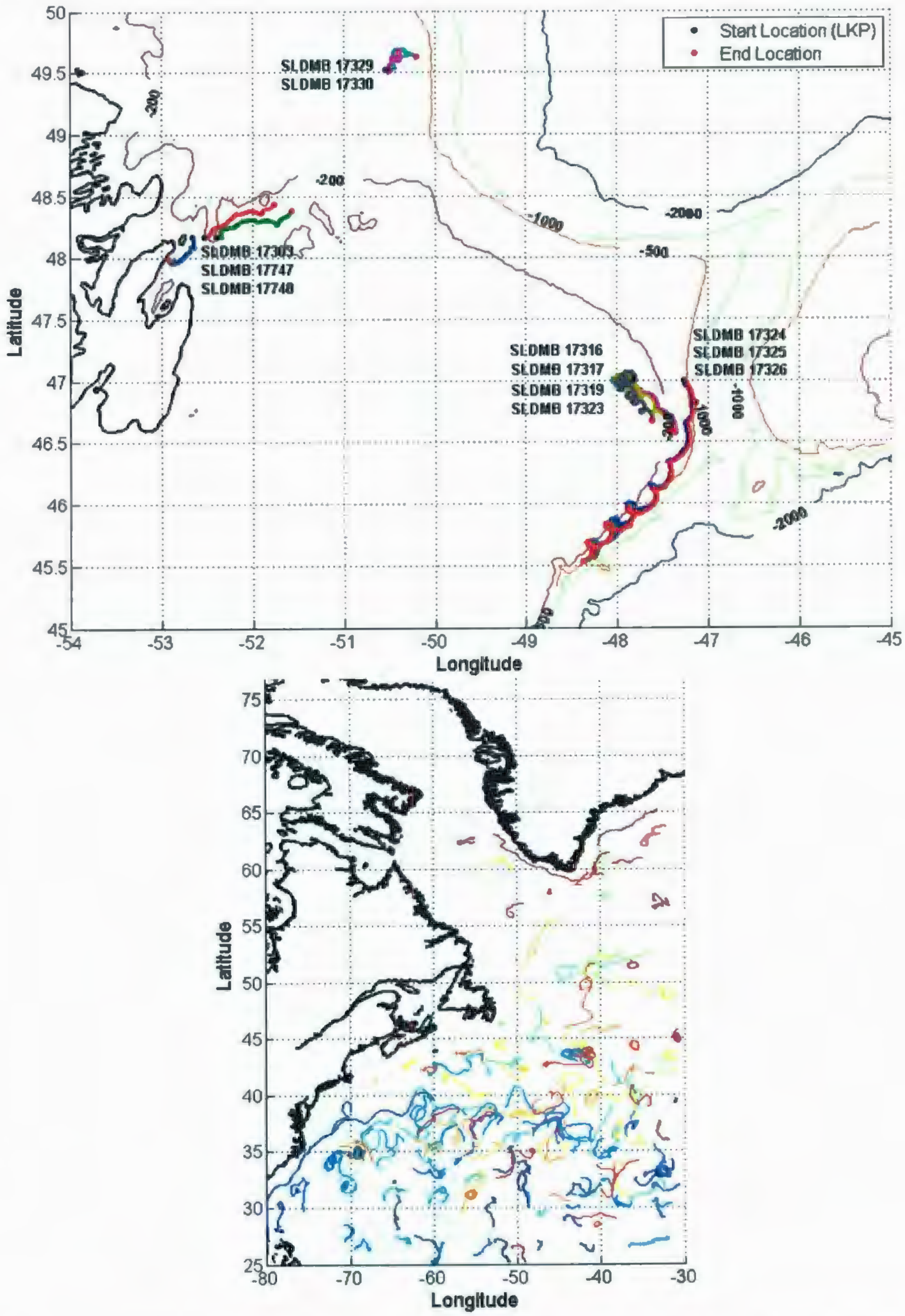

Figure 2.5 a) SLDMBs on Newfoundland shelf deployed in August of 2007. Each SLDMB is a represented by a different color and entire life spans are illustrated. Bathymetry lines are labeled and numbered in meters.
b) All available MEDS GTS drifters in the Northewest Atlantic for August 2007.

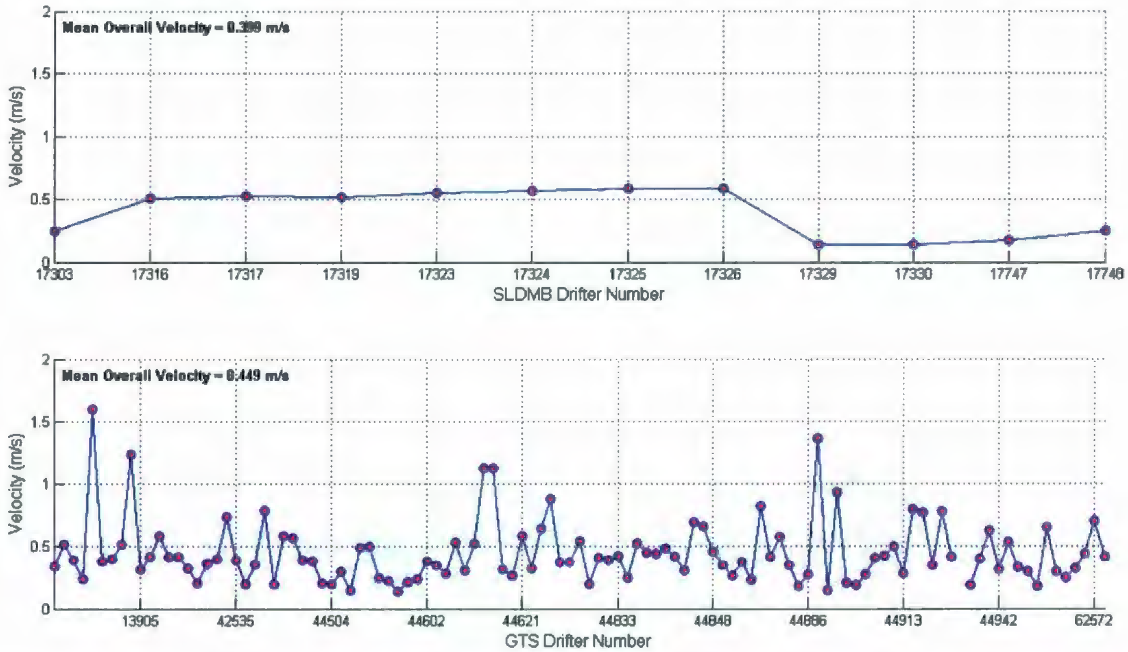

Figure 2.6 Mean velocity comparison between a) SLDMB and b) GTS drifters over their respective lifespans. Each dot represents one drifting buoy.

Experiments were done to determine whether using modeled current fields at various depths (uppermost available level and 15 m in each model) influenced drift trajectories. In the majority of cases, CANSARP Scientific under-calculates the length of the trajectory of the drifter as Figure 2.7 illustrates. As per Figures 2.8 and 2.9, minimal change is seen when currents at depths are applied whether on or off the shelf. To further this study, it was tested to see whether there is a distinctive spatial pattern between where CANSARP Scientific predicts the drifters to exist and where they actually travel in a given timeframe (48 hours in this study). It seemed that there was no pattern between location and trajectory length simulation by CANSARP Scientific, as seen in Figure 2.10 below.

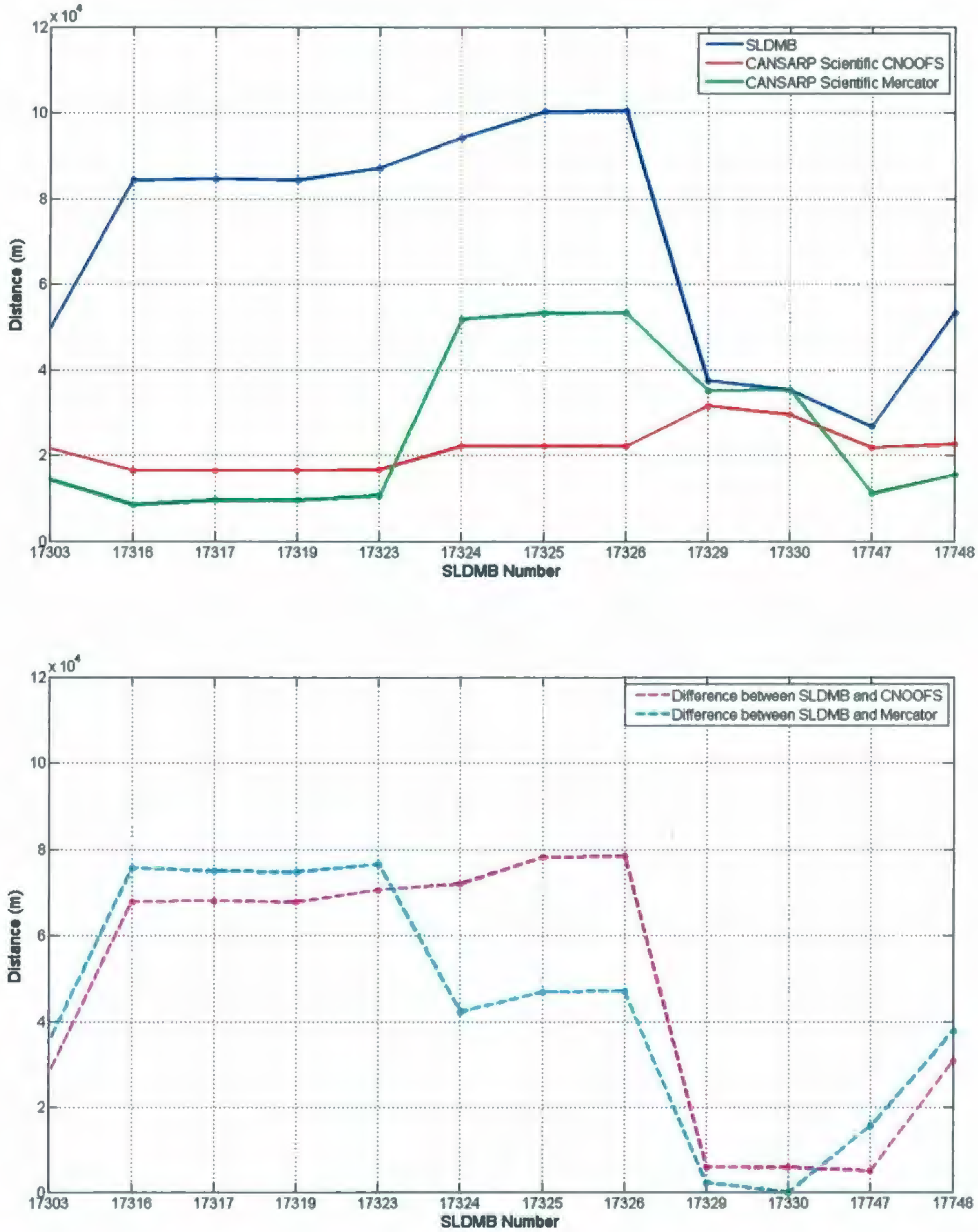

Figure 2.7 a) *Distances of total drifts of 12 SLDMBs from August 2007 for 48 hours on the Newfoundland Shelf (blue) with mean length of 70 km along with predicted CNOOFS trajectories (red) with mean length 22 km and predicted Mercator trajectories (blue) with mean length 26 km.*
b) Both current types under calculate the total distance of SLDMB trajectories. The difference in SLDMB and CNOOFS (magenta) plot has a mean of 48 km and the difference between SLDMB and Mercator (cyan) plot has a mean of 44 km. These lines are always positive indicating that the SLDMB trajectory is always longer.

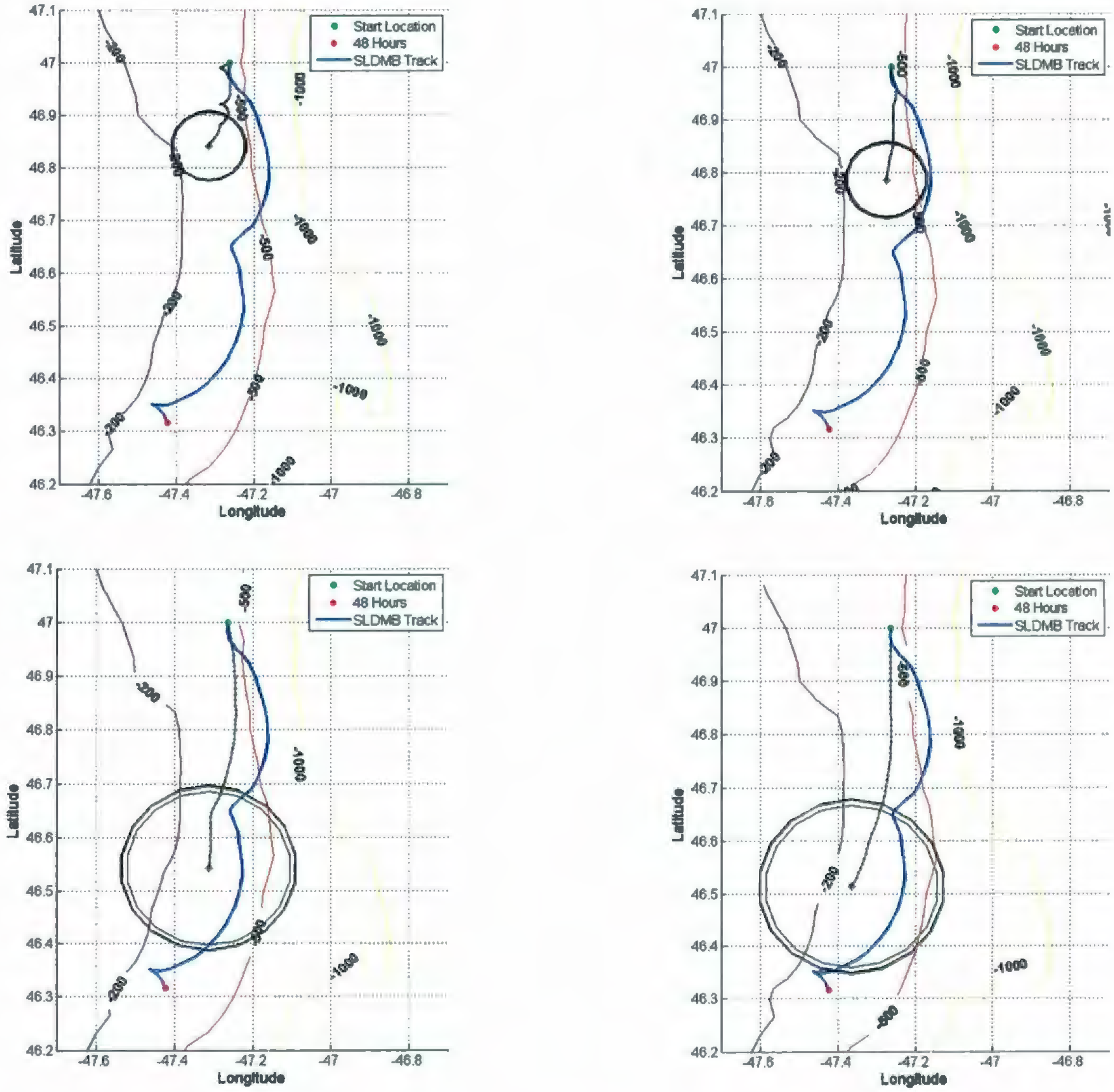

Figure 2.8 *CANSARP Scientific simulations with MinMax Method using both CNOOFS (top panels) and Mercator (bottom panels) currents at levels closest to surface (left) and 15 m (right) on the Newfoundland Shelf over 48 hours for SLDMB 17324. Blue lines represent the drifter trajectory while the black line is the predicted trajectory. Black circles indicate the search area. While some improvement is seen in total distance, resolution of drift is lost and distance is still far under calculated for all 12 cases of SLDMBs in August 2007 (by about 3 times at the surface and about 5 times at 15 m for CNOOFS currents; 2.7 times for Mercator currents at the surface, and about 2.6 times at 15 m.) This figure illustrates a unique case in the Labrador Current where the Mercator currents almost match the SLDMB trajectory.*

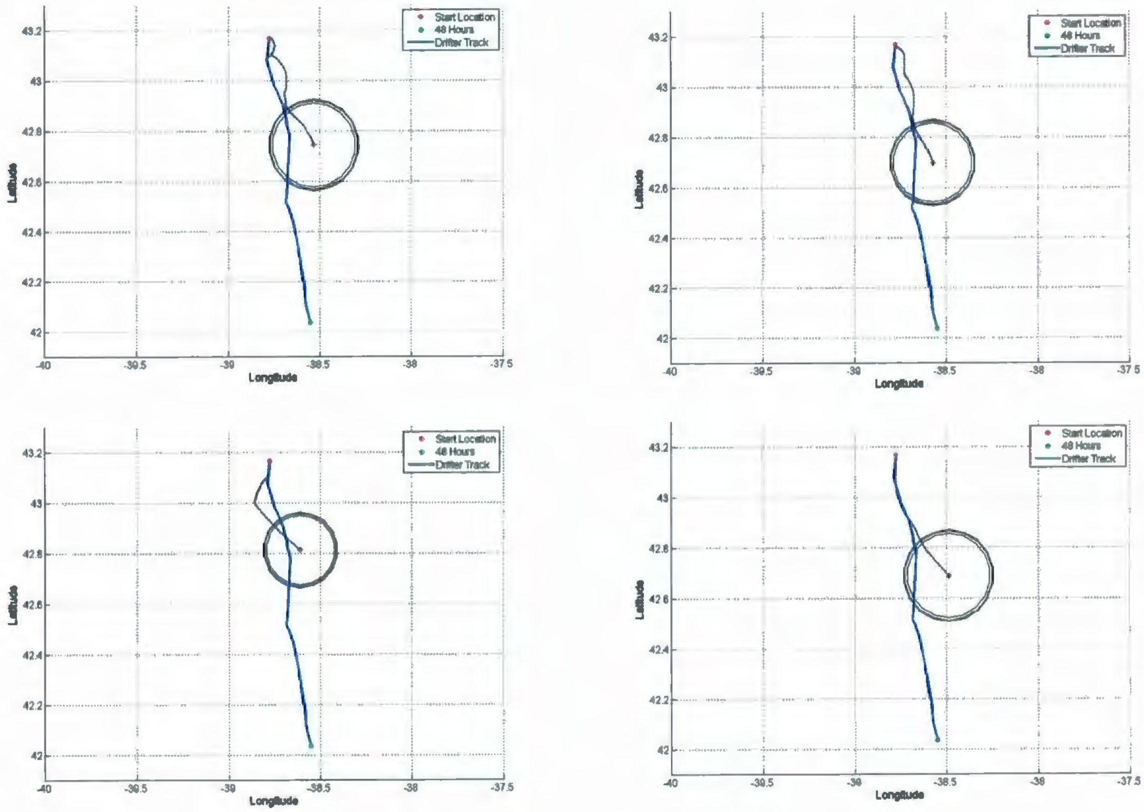

Figure 2.9 *CANSARP Scientific simulations with MiniMax Method using both CNOOFS and Mercator Currents at levels closest to surface and 15 m off the Newfoundland shelf over 48 hours. While some improvement is seen in total distance, resolution of drift is lost and distance is still far under calculated, as specified in Figure 2.8.*

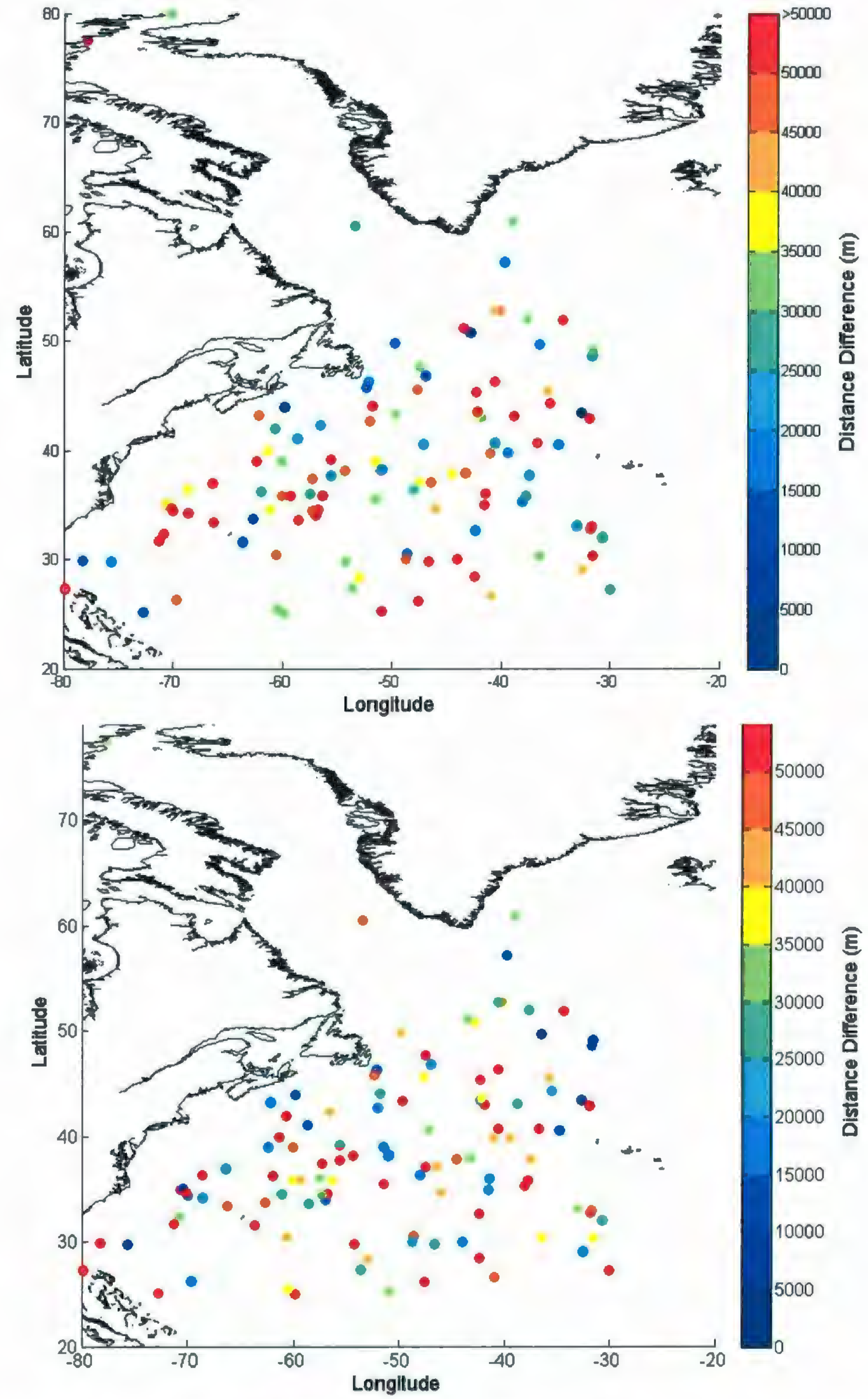

Figure 2.10 *Correlation between distance of CANSARP Scientific output using Mercator Currents at surface level and 15 m versus actual drift trajectories. No obvious patterns can be observed geographically.*

Tests were run with "continuous" versus "discontinuous" output currents from the CNOOFS model. In this context, continuous refers to a special model run producing hourly output data for the entire length of the simulation in one run. Discontinuous refers to separate model runs, re-initialized daily, producing data output files containing hourly data; the CNOOFS present standard. Again, each case underestimated the drift length of the SLDMBs, but in all cases, the discontinuous data produced longer search trajectories than the continuous data an average of 150 km. In the discontinuous data, the SLDMB tracks were about 3 times longer than the predicted trajectories while in the continuous data, they were about 4 times longer. Examples of these simulations can be seen in Figure 2.11.

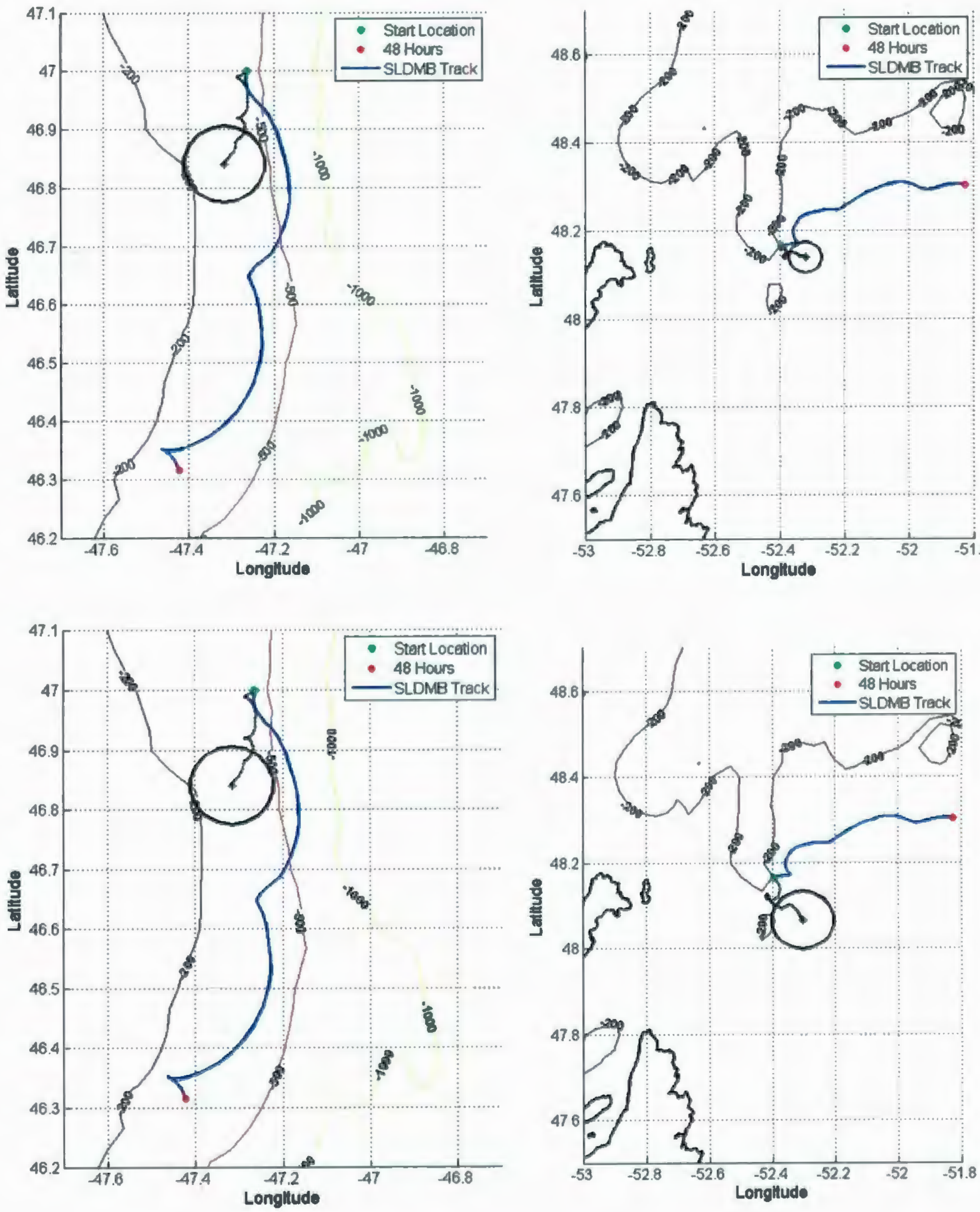

Figure 2.11 Continuous and discontinuous CNOOFS model output data used in CANSARP Scientific simulations. Top images show simulations with continuous data while bottom images show simulations with discontinuous data.

Chapter 3 Drift Algorithms

3.1 *The MiniMax Method in Canada*

The concept of the MiniMax Method used by the Canadian Coast Guard was developed by Bernard Koopman in 1949 with the intention of defining a search area with 100% containment (Koopman, 1980). As its name implies, this method calculates the minimum and maximum possible locations of the target drift object based on a number of possible uncertainties. These uncertainties can be in time, location, or drift forces (CCG/DFO, 2000). The midpoint between these two extremes is the datum point for the search. Datum is the most probable location for a search object at a given time (CCG/DFO, 2000).

Following the "datum" determination, the sum of the squares of all possible errors is calculated to represent the square of the total error (CCG/DFO, 2000). The search area size is determined based on the total error, E. There are three components that are considered in calculating the total error; the total drift error, the initial position error, and the search unit error.

The total drift error, denoted D_e, is either the combination of all individual drift errors (d_e), or is calculated as a function of the distance between the minimum and maximum locations ($d_{e\ minimax}$). Individual drift errors are cumulative throughout the drift due to assumptions that simplify calculations. The Canadian Coast Guard assigns a constant value to d_e of 1/8 of the determined drift (default) or 1/3 the determined drift if confidence on the given information is low as determined by the search coordinator (CCG/DFO, 2000). The distance between the minimum and maximum locations, also called the MiniMax drift error is calculated by:

$$d_{e\_\min i\max} = \frac{Dis\tan ce + d_{e\_\min} + d_{e\_\max}}{2} \tag{3.1}$$

where Distance is the distance between d_{min} and d_{max}, d_{e_min} is 1/8 (or 1/3) d_{min} and d_{e_max} is 1/8 (or 1/3) d_{max}. The value of D_e will usually be equal to the value of $d_{e\_minimax}$ unless multiple searches are planned in progressing time. In that case:

$$D_e = d_{e\_\min i\max_1} + d_{e\_\min i\max_2} + \ldots + d_{e\_\min i\max n} \tag{3.2}$$

Let X be the error (in meters) of the initial position based on the source reporting the Last Known Position (LKP) of the search target (CCG/DFO, 2000). When X is reported as a fixed position, it is known as the "fix error" and the position error is attributed to navigational systems indicating a position, and the dead reckoning error, based on a percentage of the distance the search target has drifted since its last reported position (CCG/DFO, 2000). The fix errors are based on a table with error values associated with respective navigation systems, and the dead reckoning errors are also indicated in a table based on the type of aircraft or vessel searching for the target (CCG/DFO, 2000). Dead reckoning values are only applied if the source of the LKP indicates they should be. Similarly, a search craft error called Y is to be applied when appropriate, and is equal to the fix error of the search craft. Total probable error is thus (CCG/DFO, 2000):

$$E = \sqrt{D_e^{\,2} + X^2 + Y^2} \tag{3.3}$$

Of course, the value of the total error E must be re-computed in time as drift changes, impacting the datum, or if the search unit or initial position changes.

Once this is complete, the search radius is implemented with radius of E around the datum point.

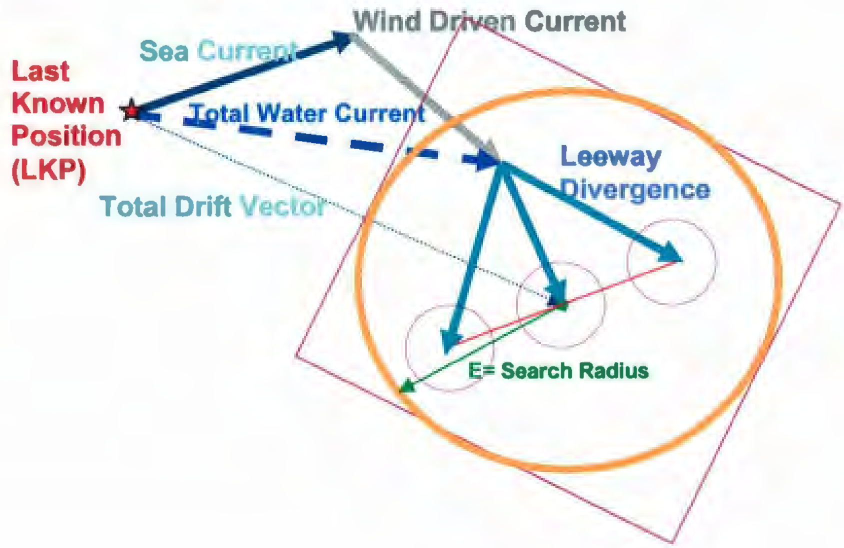

Figure 3.1 *The MiniMax Method basic diagram.*

Figure 3.1 shows that the search is based from the Last Known Position (LKP). From here, the sea current (water forces acting on the object) vectorially add with the wind driven current (water forces driven by winds) to produce a total water current. Once this new location is established, leeway divergence is applied. A lookup table for leeway divergence based on the object type search and produces leeway angles ranging from 0 to 60° to either side of downwind (CCG/DFO, 2000). Once a minimum and maximum divergence angle are established by leeway, leeway uncertainty is considered, if the total drift time is greater than 4 hours (CCG/DFO, 2000). The leeway uncertainty value is simply the distance between the minimum and maximum locations, summed with their respective confidence values and averaged which then represents the radius of each error circle. Once small error circles are established, the total error as described above is plotted around the search area, centered on the midpoint between the minimum and maximum positions from leeway divergence is produced, and a search plan, often based on a square of rectangular shape, can be decided upon by the search planner based on available resources. Of course, the search area will increase as time goes on as errors increase.

3.2 *The Monte Carlo Method*

The Monte Carlo method is a stochastic, non-deterministic algorithm that provides a statistical distribution of a solution (Fox, 1962). In the case of SAR, a probability distribution that evolves with time forms a search area of particles. Presently, although planned, the Monte Carlo Method is not used in CANSARP. In CANSARP Scientific, the Monte Carlo Method option is based on the Norwegian model entitled "LEEWAY". In CANSARP Scientific, the drift trajectory of individual drifter particles is determined in the same manner as in the MiniMax method. The difference is that there are many randomly perturbed particles with the convex hull determining the search area. At each time step, the wind and current are perturbed in magnitude and direction randomly with a component specific standard deviation. The contributed random noise is additive to the trajectory calculation. Next, the leeway coefficients have a perturbation applied to it, and leeway vectors for both crosswind and downwind are computed using linear regression formulae produced by Allen and Plourde (1999) according to the type of object drifting. The advected particle results in a component of the particle cloud for each iteration and particle required. The number of particles computed is user dependent, but the present default in CANSARP Scientific is 250.

The initial distribution of particles is determined by a separate routine that takes all particles and distributes them based on the Last Known Position of the drifter of interest. The first two particles are undisturbed, and each of the others is randomly perturbed, constrained by a radius determined from the initial position error and number of particles in the simulation. With each time step, the radius expands by an amount *dr* defined as the initial position error divided by the number of particles in the simulation less 1. Each position is displaced by a pseudorandom number selected from a normal distribution with mean 0 and standard deviation 1, and is multiplied by a coefficient (adjustable by user) with default value 0.5, multiplied by the radius of search, as determined above. This is all computed in a polar coordinate system prior to determining the drift trajectory.

This method varies considerably from that of the Norwegian SAR that initially positions all particles according to a 2D Gaussian distribution with a standard deviation equal to half of a user-specified radius. In Norway, two radii of uncertainty are applied, since the search with leeway is usually bimodal[3]. Each radius is determined in a similar way to which the Canadian search areas based on error are found (Breivik, n.d).

In CANSARP Scientific, all options for running the Monte Carlo Method are the same as in the MiniMax Method in terms of environmental inputs and initialization. Below is an example simulation using the Monte Carlo Method with CNOOFS currents for 48 hours and 250 particles, with a constant standard deviation of 0 applied to the currents and 2.0 to the winds (default settings):

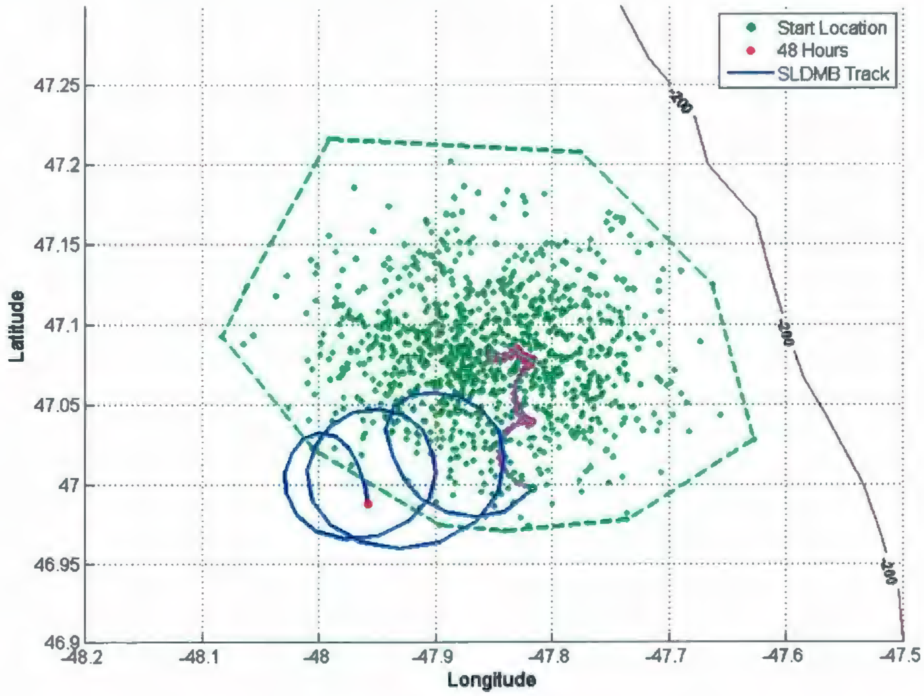

Figure 3.2 *Example Monte Carlo Simulation in CANSARP Scientific with CNOOFS currents for 48 hours using 250 particles (green dots). The dashed green line is the predicted search area by the Monte Carlo method, the solid pink lines are the predicted search trajectory by CANSARP Scientific (mean of left and right clouds of particles), and the solid blue line is the actual SLDMB trajectory. The numbered line is a line of bathymetry at 200 m depth.*

[3] In this case, bimodal refers to having two areas of equal probability and equal size.

3.3 *Drift Method Applications in CANSARP Scientific*

Several combinations of inputs can be used to run CANSARP Scientific with either of the aforementioned methods. The total water current can be determined from ocean forecast inputs or if background climatology is used, wind currents must be taken into account. In CANSARP Scientific, the CNOOFS and Mercator ocean forecast currents can be selected. If the climatological sea currents are used, the variable wind driven component of the current can be added through three alternatives; the Rule of Thumb Method, the Ekman Method, or the Madsen Method.

3.3.1 Wind Driven Component Calculation Options

The Coriolis force pushes moving objects right (left) in the Northern (Southern) Hemisphere. The faster the object moves, the more strongly it is affected by this force. As discovered by Fridtjof Nansen in 1893, both forces acting on constant water current; the Coriolis and wind force, must balance. To achieve this "geostrophic balance," the ocean current must move the water mass from the surface to about 500 m depth to the right of the wind direction while the Coriolis force pushes the water 90° to the right opposing the surface wind (Fox-Kemper, 2002).

Nansen's student, Walfried Ekman, developed a mathematical representation explaining how surface current flows, including internal forces within the water that decay at depth in an infinitely deep homogeneous ocean spiraling in an anticyclonic direction (Lenn & Chereskin, 2008). This became known as the Ekman spiral. Each of the three current estimation methods available in CANSARP Scientific are based on the Ekman theory.

The Rule of Thumb method is the simplest form of accounting for wind stress forcing and the Coriolis affect through a constant term. Here the Coriolis force can be approximated with the current magnitude at 3.3% of the wind speed and current direction 20° to the right of downwind, as in CANSARP Scientific (Fox-Kemper, 2002). This approximation holds for values of approximately 45° latitude in the Northern Hemisphere (Stewart, 2005).

The Ekman Method uses lookup table for winds, based on Ekman theory and eight 6-hr periods (0, 6, 12, 18, and 24 hours). Wind speed and direction are considered to be those which were valid at the end of the period. Based on each period's location (latitude and longitude), direction and speed, a directional offset and speed factor are extracted from tables and applied to the current direction and speed of the wind to provide an extrapolated drift prediction.

This method uses a 19-hour history of winds at the given location to calculate, based on Ekman Boundary Layer Theory (Madsen, 1976), the drift (direction and speed) due to winds. When this method was founded, its improvements on Ekman's method were that it assumed that the vertical eddy viscosity increased linearly with vertical distance from a sheared boundary, and that is could be applied in both shallow and deep waters (Madsen, 1976) – a characteristic uncommon for models of its time. Madsen (1976) discusses this calculation procedure in detail.

Table 3 contains the mean and standard deviation in the length of each of these 3 current estimation methods as compared to the actual length of the SLDMB's drift.

Table 3 Mean and Standard Deviation of Drift Length for 12 SLDMBs in August 2007 Using Current Estimation Methods Compared to Actual SLDMB Drift Length

Trajectory Type	Mean Length (m)	Standard Deviation in Length (m)
Rule of Thumb (Predicted)	2.98×10^4	4.78×10^3
Ekman (Predicted)	2.17×10^4	8.00×10^3
Madsen (Predicted)	2.52×10^4	6.03×10^3
SLDMB (Actual)	6.81×10^4	2.67×10^4

The SLMDB trajectory is 2.3 to 3 times as long as the predicted trajectory in each of the above cases, on average. This is a considerable discrepancy and the results are illustrated in Figure 3.3.

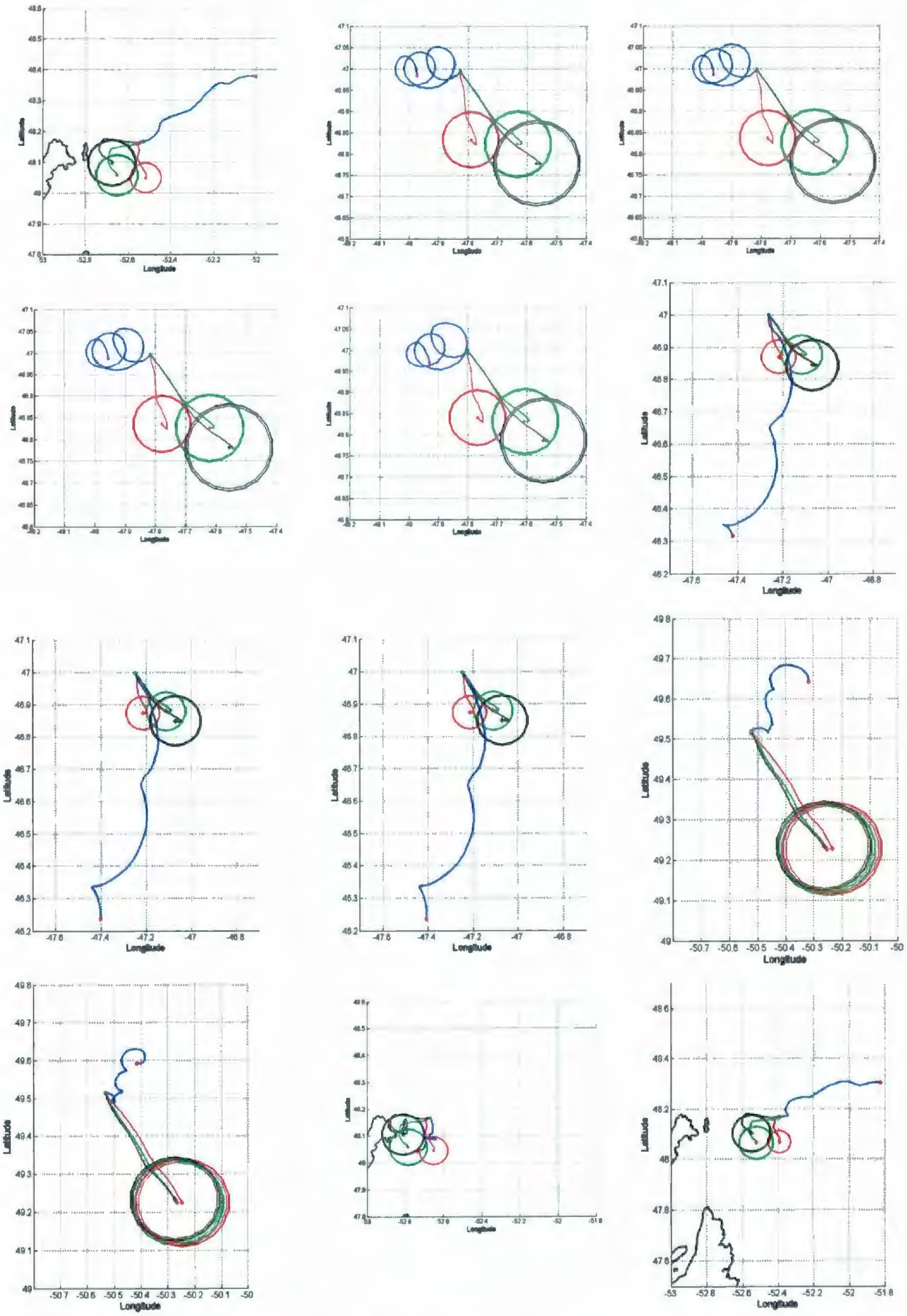

Figure 3.3 Rule of Thumb (black circles), Ekman (red circles), and Madsen (green circles) current estimation algorithm outputs as they exist in CANSARP Scientific on 12 SLDMBs from August 2007 over 48 hours. Blue lines are SLDMB tracks punctuated by a green dot at the start and a red dot at the end of the drift. Actual positions relative to landmasses and bathymetry can be seen in Figure 2.5a.

3.4 *Additional Current Approximation Algorithm: The Pollard-Millard Method*

The present methods of current estimation in CANSARP and CANSARP Scientific do not consider inertial oscillations[4]. To test the impact this change may make, the Pollard-Millard algorithm was implemented into CANSARP Scientific. Pollard and Millard (1970) proposed that most inertial oscillations at the sea surface could be attributed to winds, and applied the linear momentum equations of the mixed layer to explain wind-stress induced currents caused by wind stress considered as a body force. These equations are:

$$\frac{\partial u}{\partial t} - fv = F - cu$$

$$\frac{\partial v}{\partial t} - fu = G - cv$$

where $\frac{\partial u}{\partial t}$ and $\frac{\partial v}{\partial t}$ are acceleration terms, f is the inertial frequency, $-cu$ is the linear damping or friction term, and F and G are wind stress terms solved iteratively as follows:

$$(F_i, G_i) = \frac{\rho_a C_D U_i^2}{\rho_w Z_0}(\sin\theta_i, \cos\theta_i) \tag{3.4}$$

[4] A periodic motion in which the fluid inertia is balanced by the Coriolis Force. Inertial oscillations are dependent upon their latitude position and travel clockwise in the northern hemisphere and counterclockwise in the southern hemisphere. They are the most common currents in the ocean, and are caused by fast changes in winds at the sea surface (Stewart, 2005).

where $(U_i \sin\theta_i, U_i \cos\theta_i)$ are hourly averages of wind velocity, C_D is the drag coefficient, ρ_a is the density of air, ρ_w is the density of sea water, and Z_0 is the depth of the mixed layer (Pollard & Millard, 1970).

By incorporating the Pollard-Millard equations into CANSARP Scientific, an oscillatory pattern is generated similar to observed drifter track behavior. Winds were CMC GEM, updated hourly, from which wind stress is calculated. The resulting effect is projected onto the climatological currents. These oscillations are not accounted in the steady state methods of Rule of Thumb, Ekman, and Madsen. While oscillations are obtained, drifter track length remains underestimated, as is evident in Figure 3.4:

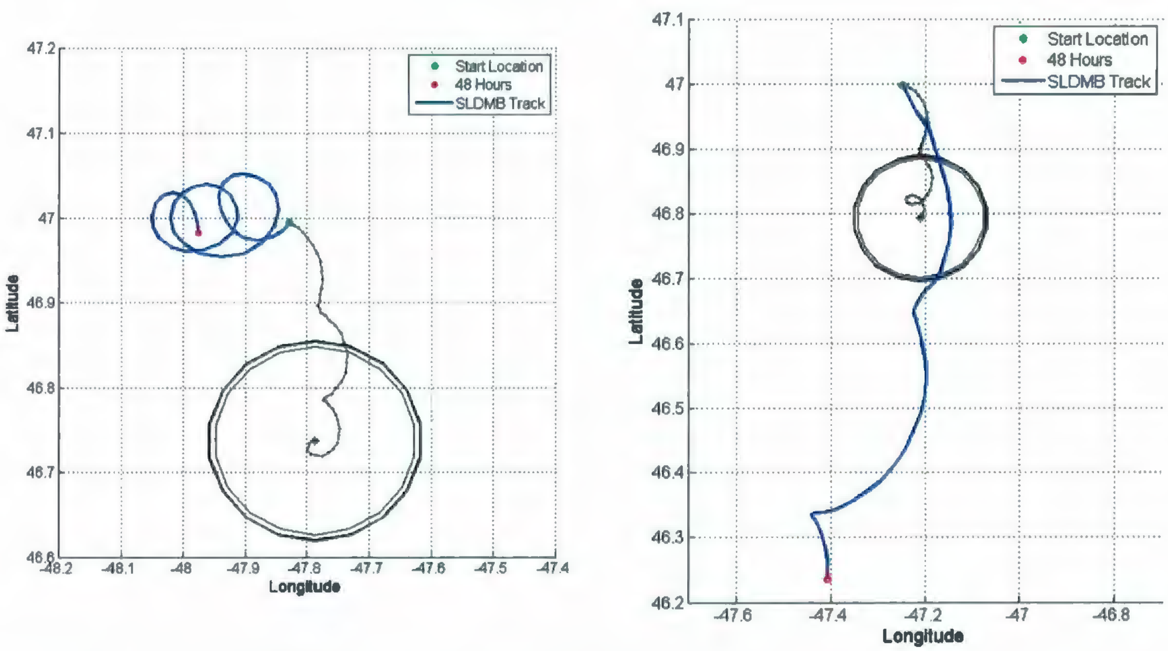

Figure 3.4 *Sample Pollard Millard Simulations for 48 hours with SLDMBs 17316 and 17326. Blue lines are SLDMB tracks while black lines and circles represent the predicted Pollard Millard trajectory and search area, respectively. Predicted trajectories are 2 to 3× shorter than actual trajectories.*

Chapter 4 Validation of Environmental Inputs and Current Estimation Algorithms

CANSARP Scientific implementations were tested including environmental inputs and existing algorithms. Reviewed first were the algorithms for estimating the drift including the Rule of Thumb, Ekman and Madsen methods. The approach used was to apply constant wind current values of 0 m/s for u and v to observe the direction and distance each drift by applying a constant current value. For example, the v component of the current was held at 0 while the u value was given a value of 0.1 m/s. If the drift traveled directly east, its direction was validated. The distance was calculated using $d = V / t$ where d is the distance, V is the velocity (0.1 m/s in this case), and t is the time. For a one hour period, the expected distance is 360.00 m. By running a simulation in CANSARP Scientific, it was observed that the direction is directly east with a magnitude of 361.32 m. The results were accurate in this case, and the Matlab functions used to read current files were considered to be validated.

Wind currents were validated in a similar manner. Currents were held constant at 0 m/s and one component of the wind vector was given a speed. In this case the direction should appear opposite to that of when currents are applied. Originally, it was found that wind currents were being offset by 180° as a result of being read in the same way as sea currents. This issue was rectified by altering the code to account for the different conventions.

Next each wind current estimation algorithm was reviewed with the corrected wind convention and constant (zero) sea currents. Manual calculations were completed to verify the Rule of Thumb and Ekman methods, according to the National SAR Manual's worksheet. Since the Madsen method has no accompanying calculations in the manual and uses look-up tables in CANSARP Scientific, any results in relative agreement with the Ekman method were taken to be acceptable for validation purposes. Results from these tests are seen in Figure 4.1.

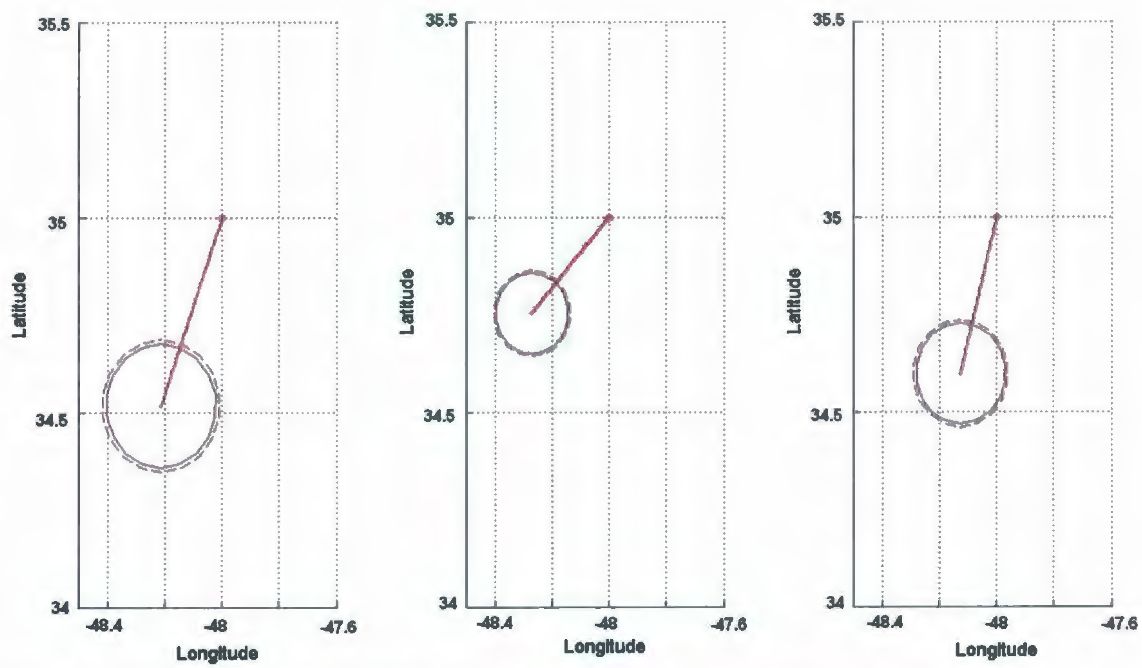

Figure 4.1 *Rule of Thumb, Ekman, and Madsen current estimation methods with wind $V = 10$ m/s and $U = 0$ m/s. Methods illustrate calculated trajectory velocities of 0.328 m/s, 0.2148 m/s and 0.2662 m/s, respectively.*

Once the direction and distance were verified in these basic plots, the application of model currents from CNOOFS and Mercator were tested. Comparisons were made by feather plots and frame-by-frame trajectory progressions in an effort to gauge whether the

CANSARP Scientific calculations and the actual drift trajectories matched the input currents. In Figure 4.2, the top panel illustrates manually extracted currents from the CNOOFS current data file over 48 hours. These values were selected based on the CANSARP Scientific calculated trajectory of SLDMB 17316. For each point in the trajectory, the nearest U and V components were extracted from the data file and plotted. Contrastingly, in the lower panel, extraction by CANSARP Scientific using nearest neighbor interpolation is illustrated. These currents are the ones applied to predict the search trajectory in CANSARP Scientific. The mean difference in direction between Figure 4.2 a and b is 42.41° with a mean velocity magnitude difference of 0.035 m/s.

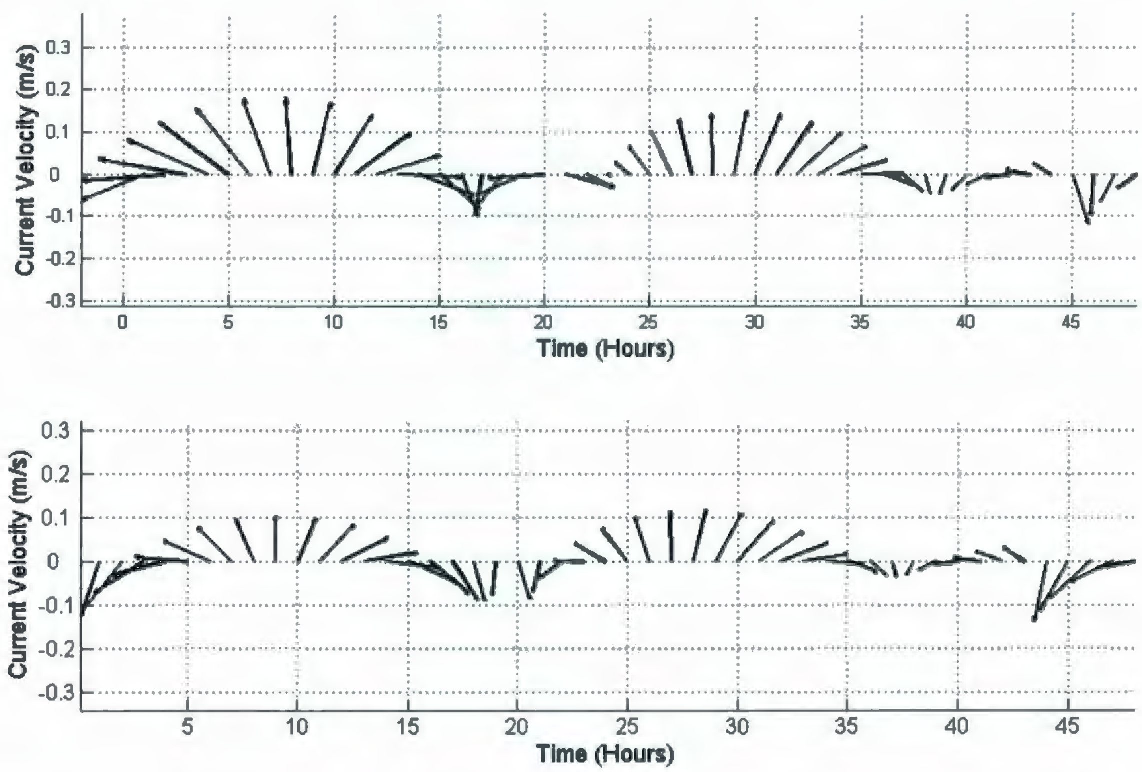

Figure 4.2 a) *CNOOFS manually extracted currents and b) calculated current output from CANSARP Scientific for a simulation at (-47.829, 46.995) starting on August 4, 2007 for 48 hours. Note that north is up.*

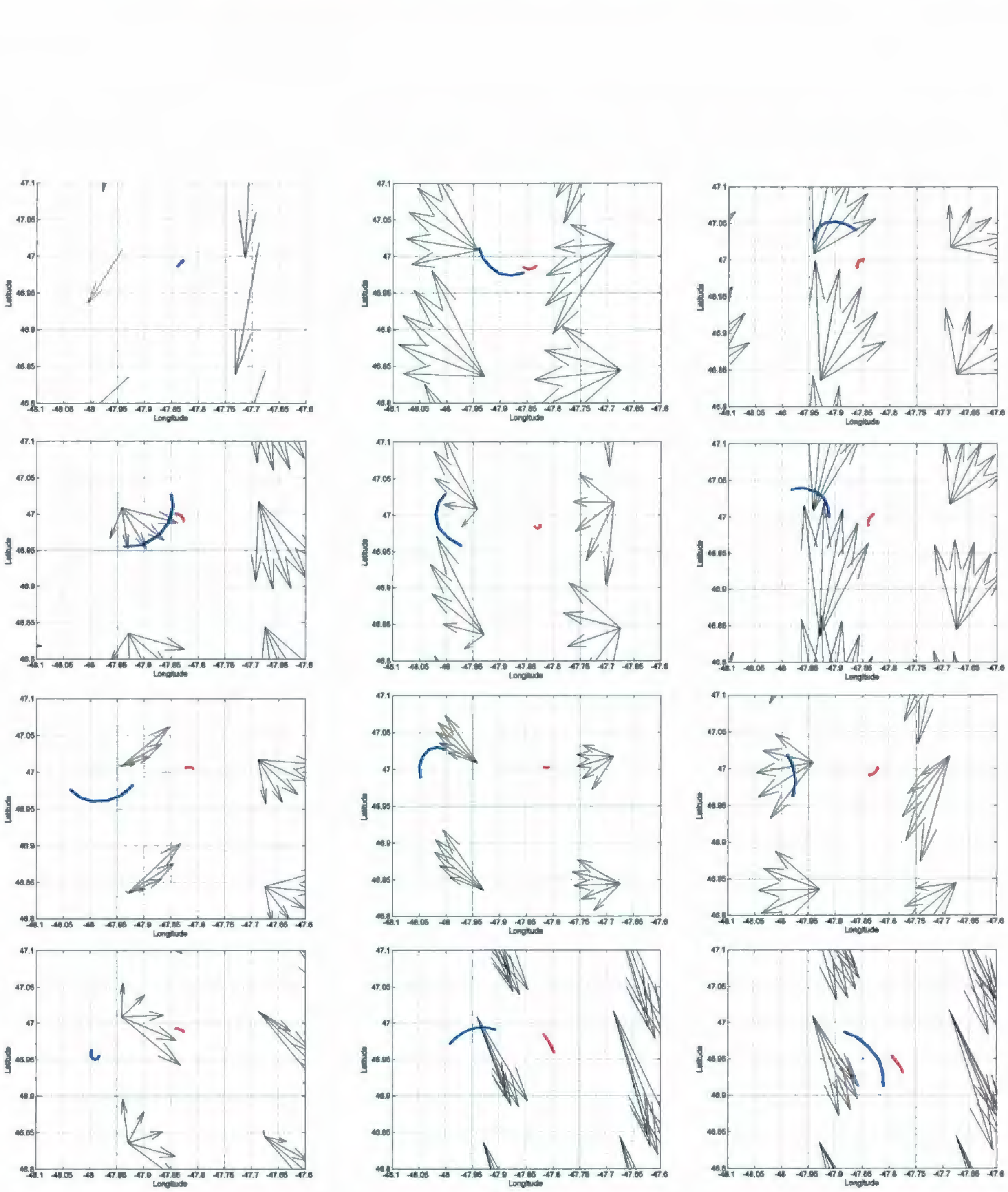

Figure 4.3 *Simulation of SLDMB 17316 on starting on August 4 at 0500Z for 96 hours at 6-hour intervals (displaying first 67 hours). The blue line represents the SLDMB Trajectory, the red line represents CANSARP Scientific's calculated trajectory and the grey quivers are CNOOFS current vectors..*

In Figure 4.2, the feather plots shows minor differences that may be accounted for in the different methods of data extraction, however, the direction and magnitude are in reasonable agreement. In Figure 4.3, while the calculated trajectory by CANSARP Scientific was not identical to the actual SLDMB data, the direction of the output trajectory does agree with the applied CNOOFS current directions in time. The average difference in direction in the SLDMB trajectory versus the CANSARP Scientific predicted trajectory is 100.50° while the average difference in distance is 1.66×10^3 m.

Similarly, the Mercator currents were verified graphically as in Figure 4.4 and Figure 4.5 where the mean directional difference between the two cases is 64.69° and the mean velocity magnitude difference is 0.0075 m/s.

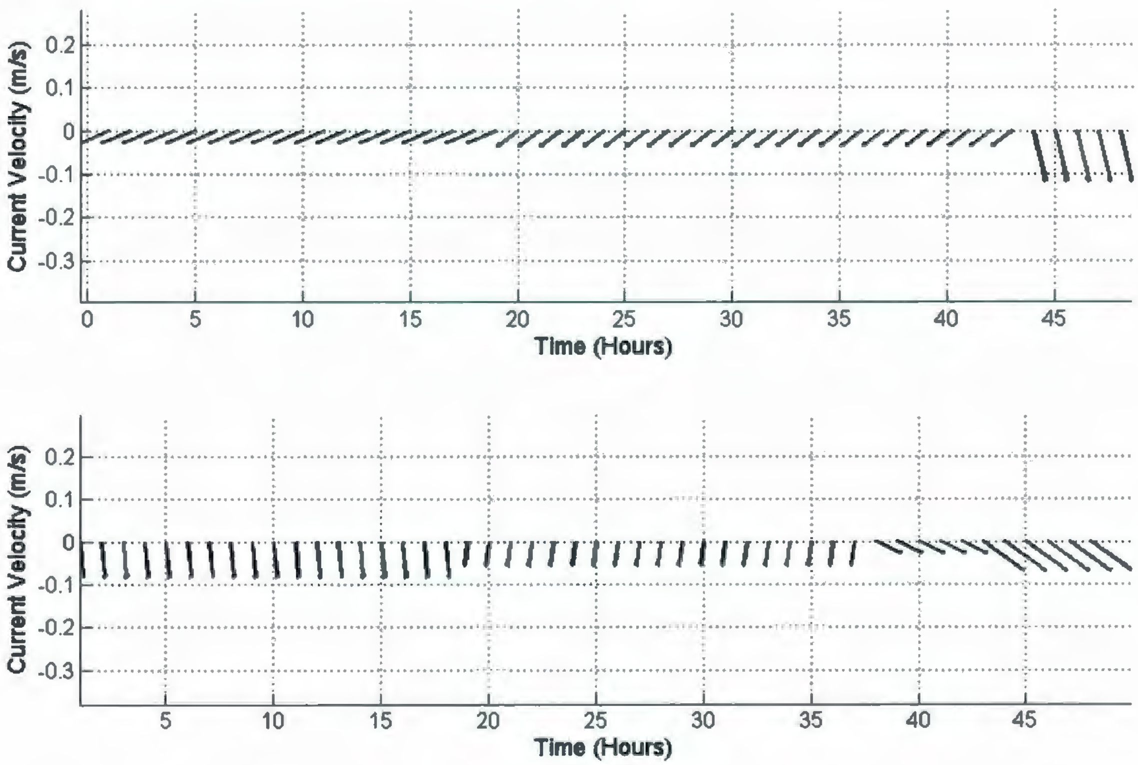

Figure 4.4 a) *Mercator Currents and b) calculated current output from CANSARP Scientific for a simulation at (-47.829, 46.995) starting on August 4, 2007 for 48 hours. Note that north is up.*

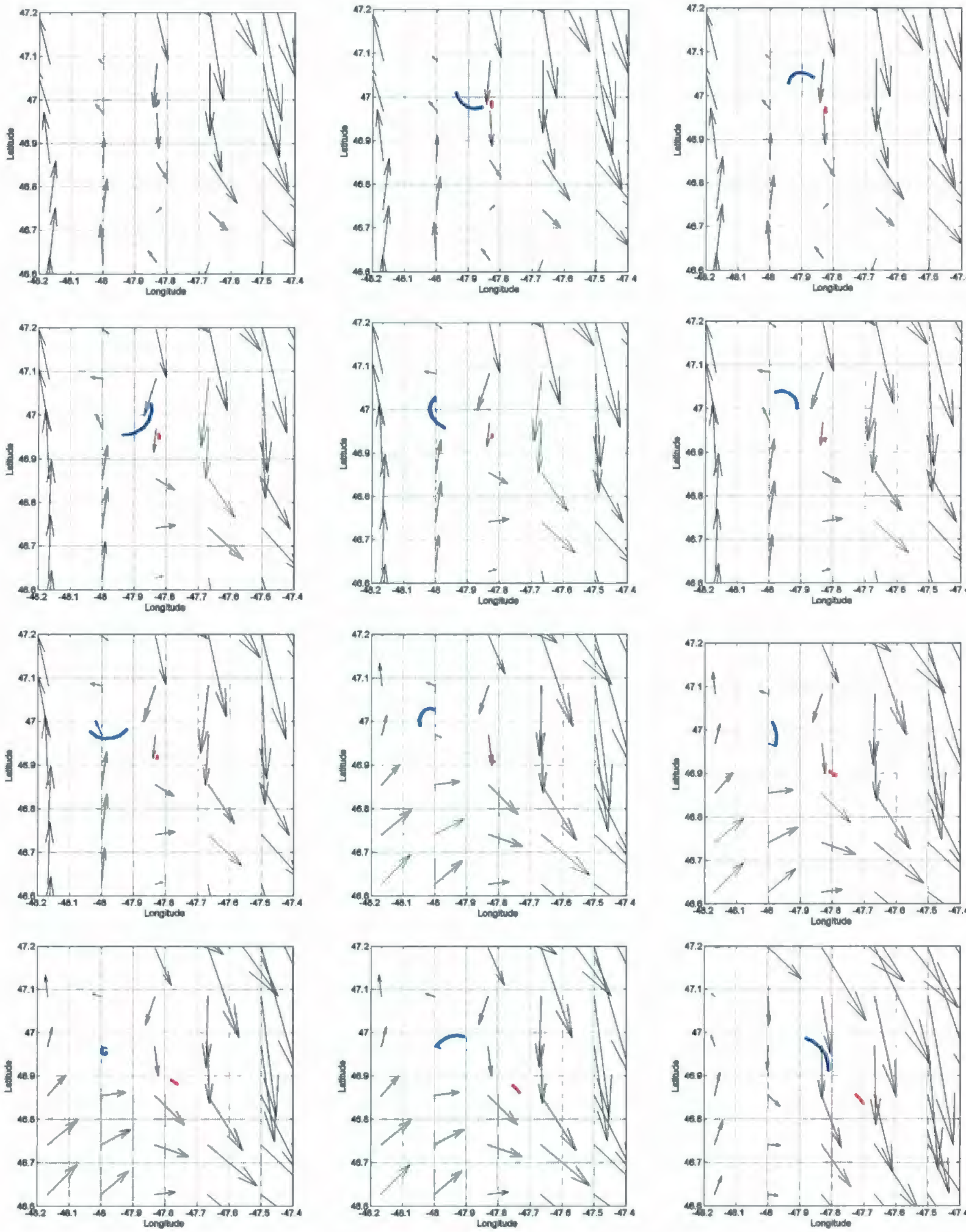

Figure 4.5 *Simulation of SLDMB 17316 on starting on August 4 at 0500Z for 96 hours at 6-hour intervals (displaying first 67 hours). The blue line represents the SLDMB Trajectory, the red line represents CANSARP Scientific's calculated trajectory and the grey quivers are Mercator current vectors.*

Like the CNOOFS currents, differences are evident in Figure 4.4 due to extraction methods. In the first panel, the Mercator currents are manually extracted based on the positions of the trajectory of SLDMB 17316; the nearest *U* and *V* components were extracted from the data file. In the second panel, extraction by nearest neighbor interpolation is seen. Quivers illustrated in Figure 4.5 are more sparse than in Figure 4.3 as a result of the time intervals in the data; Mercator data varies every 6-hours whereas the CNOOFS data varies hourly, producing a more dynamic search trajectory. Here the average difference in direction in the SLDMB trajectory versus the CANSARP Scientific predicted trajectory is 82.60° while the average difference in distance is 1.13×10^3 m.

The next verification was of the Monte Carlo method. This process was fairly straightforward since the Monte Carlo trajectory is calculated in the same way as MiniMax. In the CANSARP Scientific Monte Carlo method, the search area is determined by randomly dispersing a defined number of particles such that the mean of all the particles indicates the most likely location for the drifting object being sought after. Accordingly, the mean of the cloud of dispersed particles was determined to ensure that the search area was appropriate to the calculated drift. The mean point calculated by the CNOOFS currents is at (46.98, -47.83) while the mean point produced by the Mercator currents is at (46.95, -47.83). The calculated Root Mean Squared Error of the distributed points to the mean for CNOOFS is 334.56 m while for the Mercator currents it is 459.28 m, thus the Mercator simulation produces a slightly larger search area. The mean search radius for the CNOOFS currents was 1.69×10^3 m and 2.25×10^3 m for Mercator. This would produce a maximum search circle of about 16 km^2. The feasibility of searching this area will depend on a number of factors including the number and type of search units available, and their location, but this size is generally a non-issue. The MiniMax search area for the same scenario averages 24.5 km^2

Figure 4.6 illustrates the mean particle location and the distributed particles using both current sets:

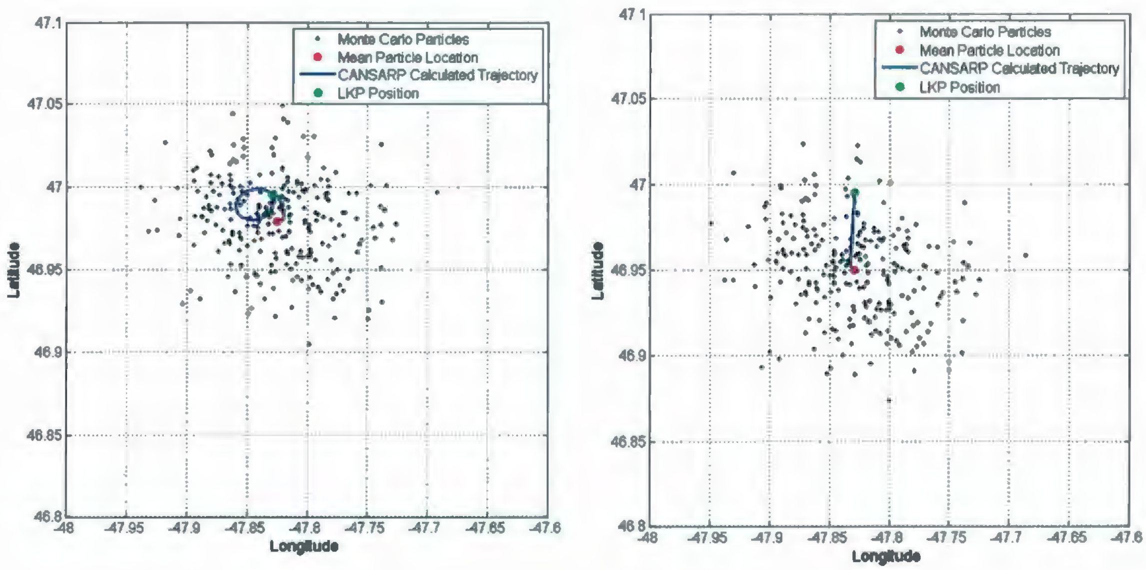

Figure 4.6 *Mean position of 250 particles after 24 hours of drift with SLDMB 17316 using the Monte Carlo method for the a) CNOOFS and b) Mercator Currents.*

Analysis (Figure 4.6) shows that the mean particle location is indeed at the end of the CANSARP Scientific calculated drift trajectory, and is situated in the middle of all randomly generated particles indicating that the determined search area is centered appropriately compared to the MiniMax method.

Finally, the drift trajectories were verified using 12 SLDMB drifters from August 2007 by comparing the MiniMax Method output to the Monte Carlo Method output. Figures 4.7 – 4.10 show these trajectories:

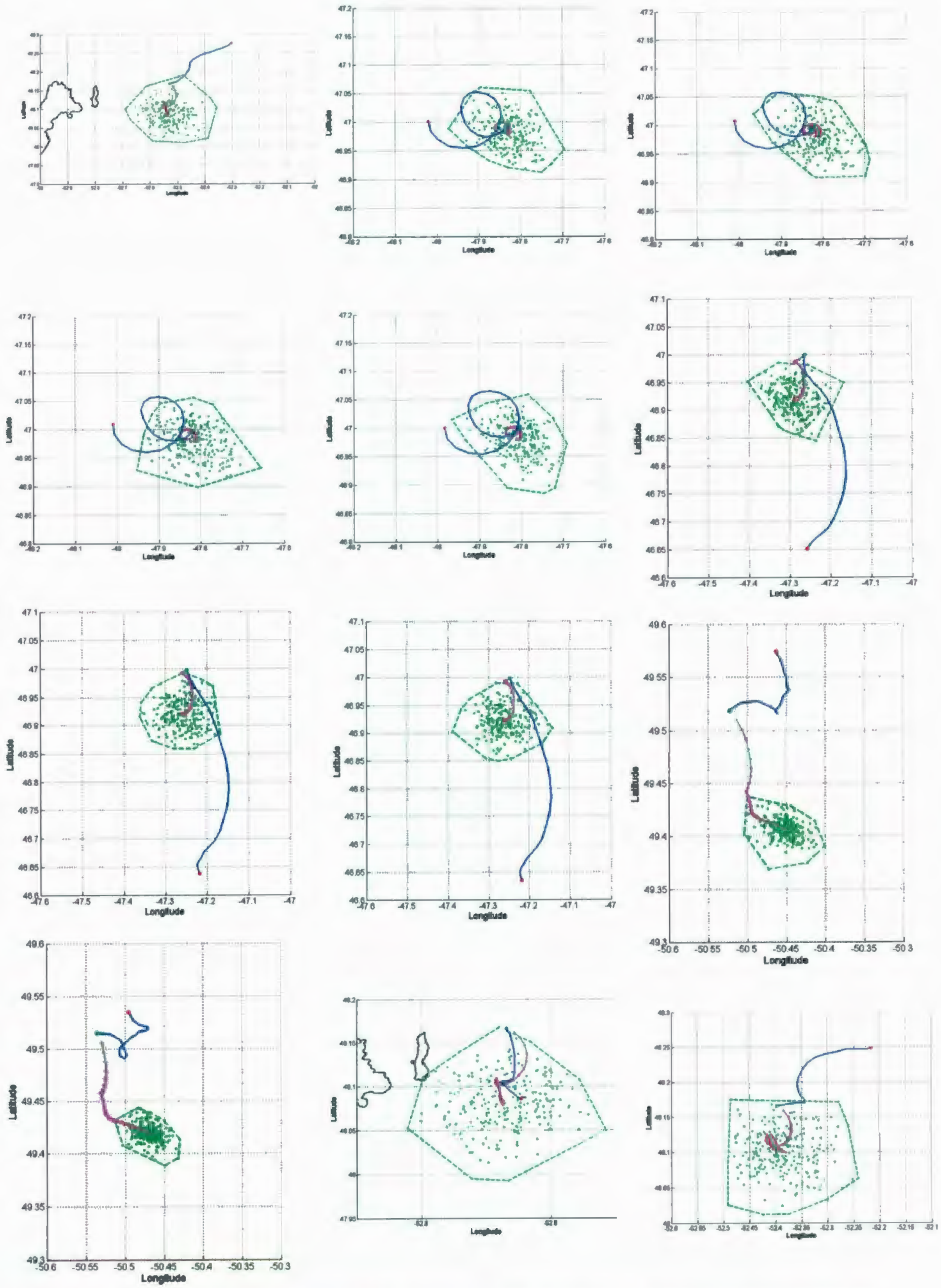

Figure 4.7 *SLDMBs from August 2007 simulated with 24-hours of CNOOFS currents using the Monte Carlo Method with 250 particles.*

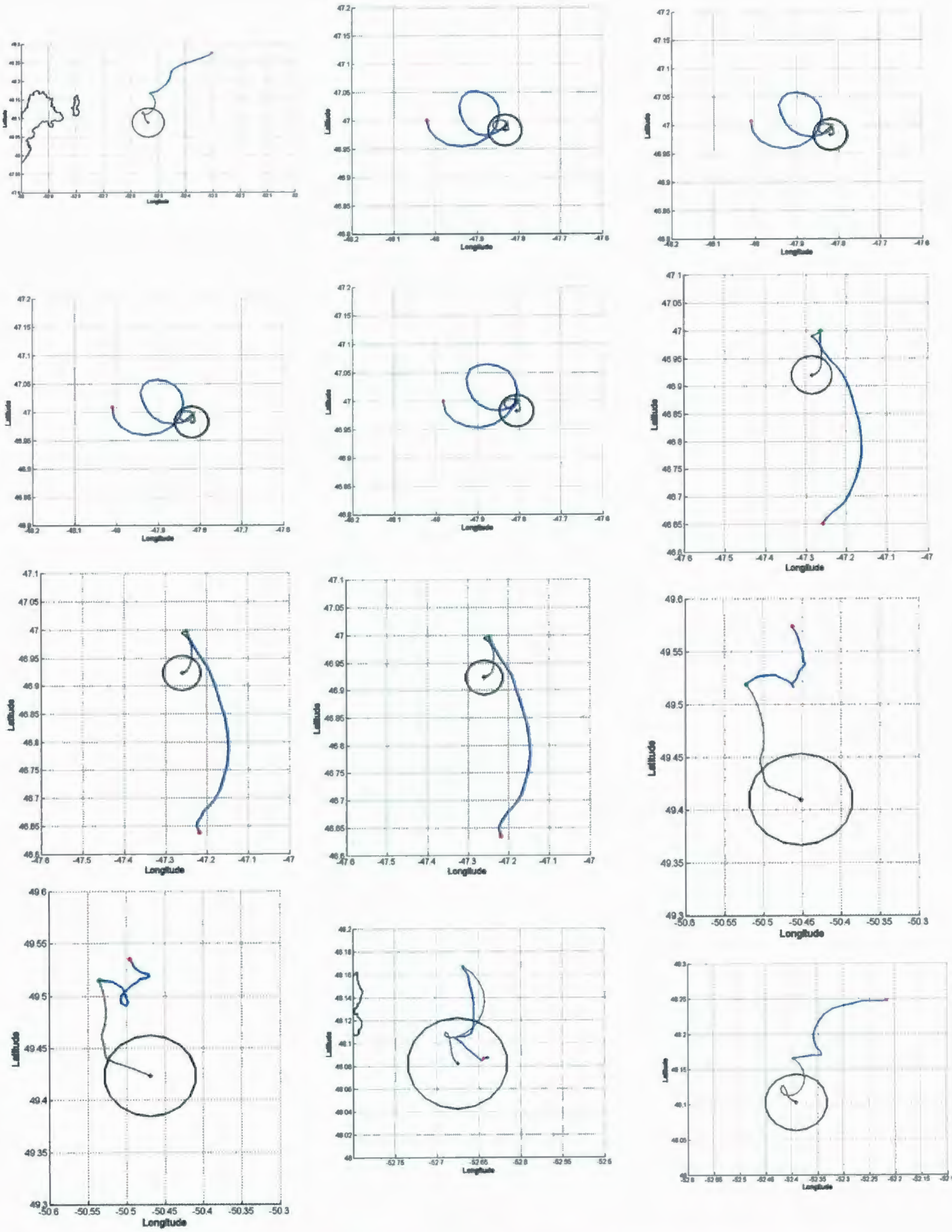

Figure 4.8 *SLDMBs from August 2007 simulated with 24-hours of CNOOFS currents using the MiniMax Method. See Figure 2.5a for location with respect to bathymetry.*

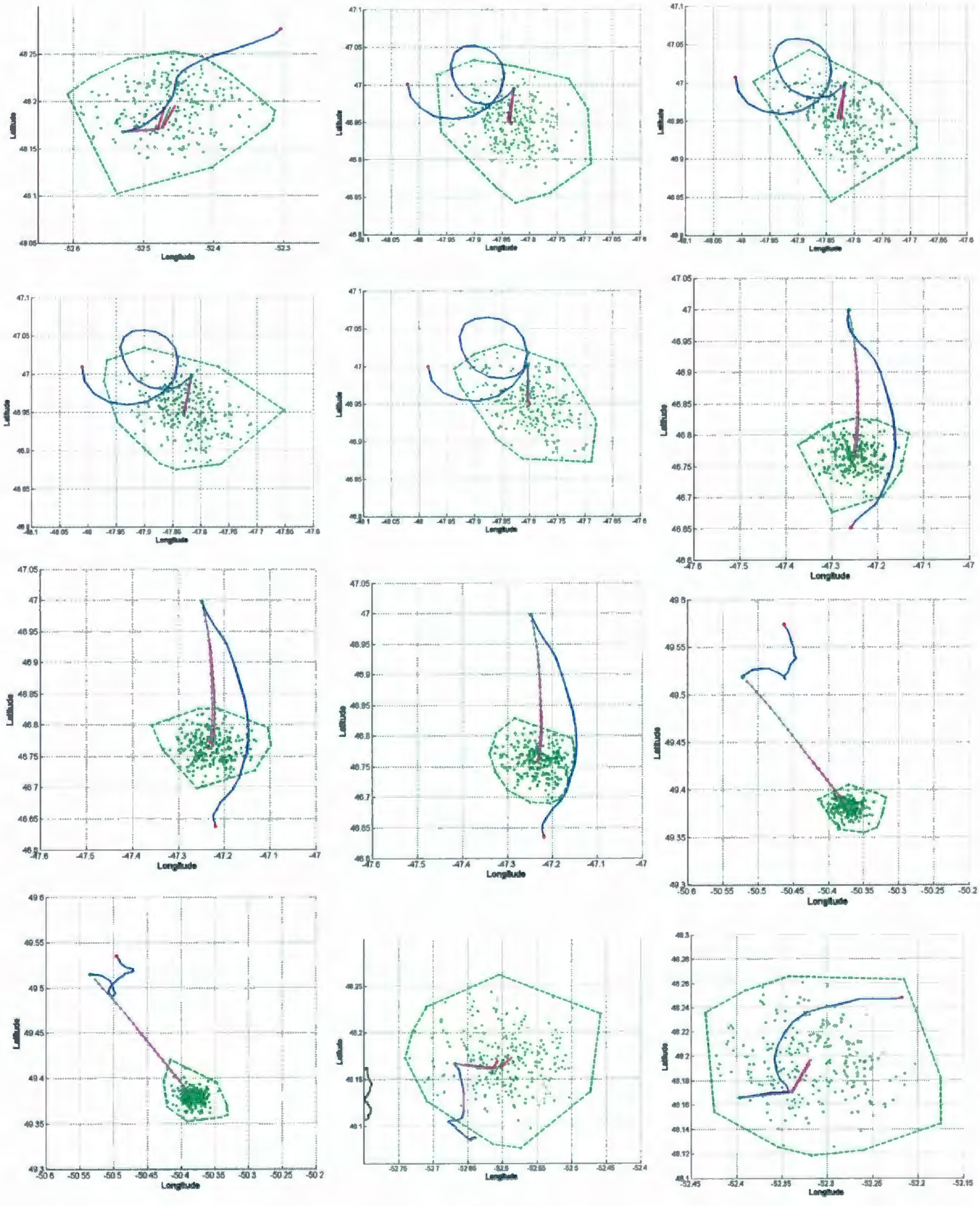

Figure 4.9 *SLDMBs from August 2007 simulated with 24-hours of Mercator currents using the Monte Carlo Method with 250 particles.*

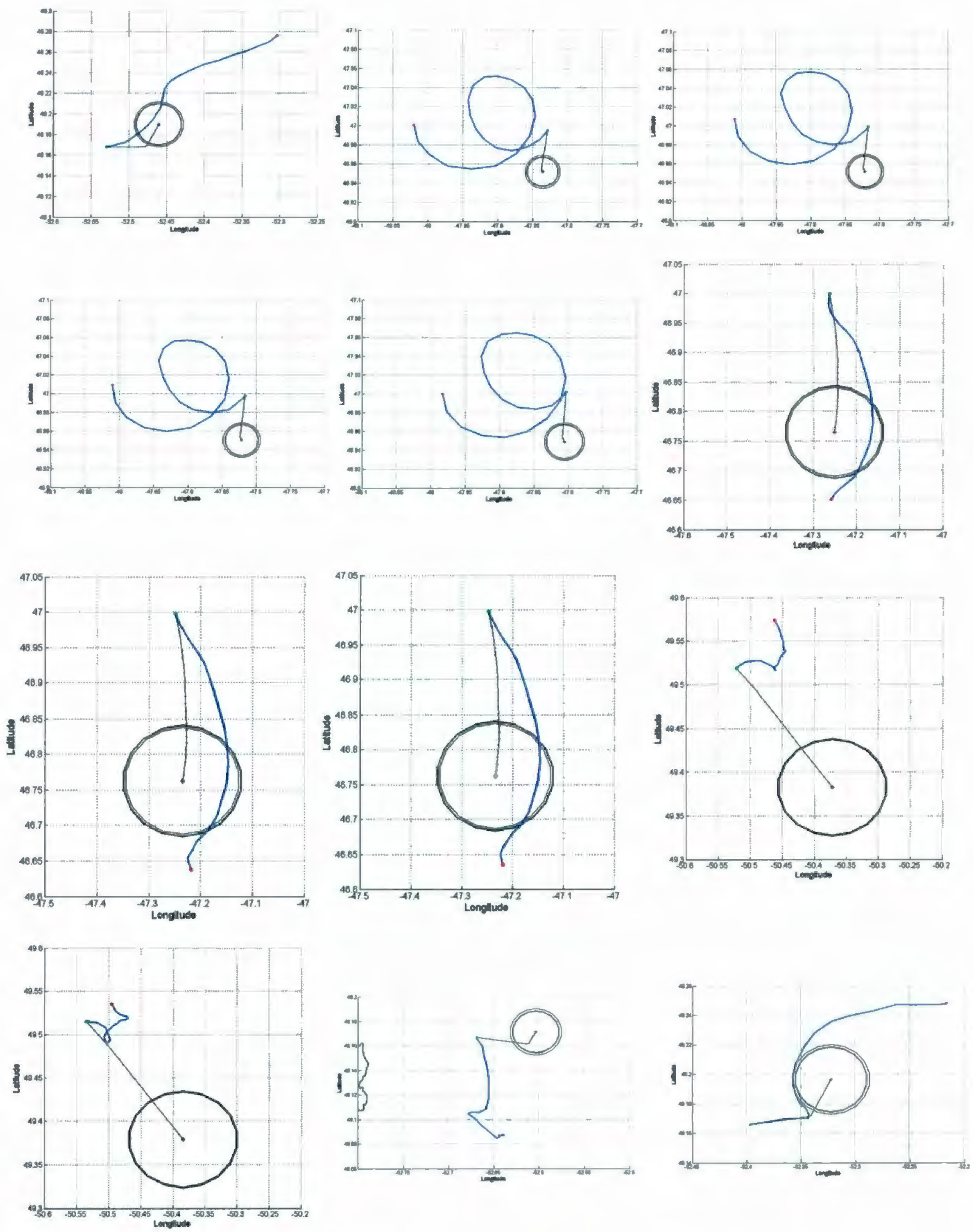

Figure 4.10 *SLDMBs from August 2007 simulated with 24-hours of Mercator currents using the MiniMax Method. See Figure 2.5a for location with respect to bathymetry.*

In each of the above figures, the calculated trajectories agree for both the MiniMax method and the Monte Carlo method, and thus the implementation Monte Carlo method was considered validated with respect to MiniMax.

In 2006, C-CORE worked with Oceans Ltd. and the Canadian Coast Guard to validate the CANSARP Scientific implementation of the Monte Carlo algorithm. In these tests, all uncertainty parameters were set to zero (downwind and crosswind leeway standard deviation, sea current components standard deviation and wind components standard deviation), and the leeway divergence coefficient was changed to 1 to produce the largest spread of particles possible (Choisnard, 2006). Winds were taken from the CMC GEM Regional model and sea currents from the climatological grid, with wind driven current calculated according to the Rule of Thumb Method (Choisnard, 2006). From the 18 tests conducted, conclusions indicated that the difference between two simulation positions is usually less than 2 km when the drift is less than 24 hours (Choisnard, 2006). It was concluded that the Monte Carlo code in CANSARP Scientific produces a result reasonably similar to CANSARP, based on these experiments.

Chapter 5 Exploring Issues and Possible Change for CANSARP Scientific

5.1 *Drift Prediction Length Issue*

After observing a number of simulations by CANSARP Scientific, it became quite obvious that the searches generated were too short in length to reasonably predict the drifter trajectories. The following sections will examine the underestimation of length using a number of approaches, and will discuss possible ways to improve this issue.

5.1.1 Current Velocity Comparison at Depths

Throughout this project, ¼° CNOOFS model output currents were being used in CANSARP Scientific with a depth-averaged current velocity from 1 to 6 meters. At the point that these experiments were run, a higher resolution version of the model was being implemented with a surface velocity field, and it was of interest to us to determine whether these higher resolution sea-surface data files would improve the search trajectory produced by CANSARP Scientific. While the new model output data was not ready to test in this thesis, an attempt to explore the impact of physical processes that govern the surface layer dynamics and the role of the surface layer Ekman transport was taken into account. This was done by calculating the Ekman velocity components according to Kundu (1990) equations 5.1 and 5.2, and comparing these values to those extrapolated in the presently applied CNOOFS data.

$$u = \frac{\tau/\rho}{\sqrt{f\nu_v}} e^{z/\delta} \cos\left(-\frac{z}{\delta} + \frac{\pi}{4}\right) \tag{5.1}$$

$$v = -\frac{\tau/\rho}{\sqrt{f\nu_v}} e^{z/\delta} \sin\left(-\frac{z}{\delta} + \frac{\pi}{4}\right) \tag{5.2}$$

In equations 5.1 and 5.2, u and v are the horizontal and vertical components of current velocity from the CNOOFS model, τ represents the wind stress calculated from the CMC GEM Winds data at the time and location of the simulation, z is the depth from 0 to 100 m, and ρ is the density of water, taken to be 1027 kg/m^3. The Coriolis Parameter, f, is calculated as $f = 2\Omega \sin\lambda$ where Ω is 7.292×10^{-5} s^{-1} and λ represents the latitude of observation, and δ, the thickness of the Ekman Layer is determined as $\delta = \sqrt{\frac{2\nu_v}{f}}$ where V_v is the eddy coefficient taken to be constant at 0.01 m^2/s, as per Kundu (1990).

The Ekman velocities were computed for 1 – 100 m depth from τ (the wind stress). If the calculated wind speeds are high, then the surface current is probably affected substantially by winds, thus accounting for the large (approximately 3× larger) drift produced by CANSARP Scientific versus the SLDMB trajectory. If this were the case, then the CNOOFS model, which only has a surface layer resolution of 5 m may not be defining the surface currents with sufficient resolution.

Plots were generated for each of the 12 SLDMB LKP positions and times in August 2007 for 1-hour intervals in the CNOOFS data. There were also sample plots done at (38, -55), (40, -45), (40, -55), (40, -65), (55, -55), for both CNOOFS and Mercator data on August 7, 2007 at 01:00. These samples represent locations in the Labrador Current and within the sub-polar and sub-tropical gyres. A sub-sample of these plots is illustrated in Figure 5.1.

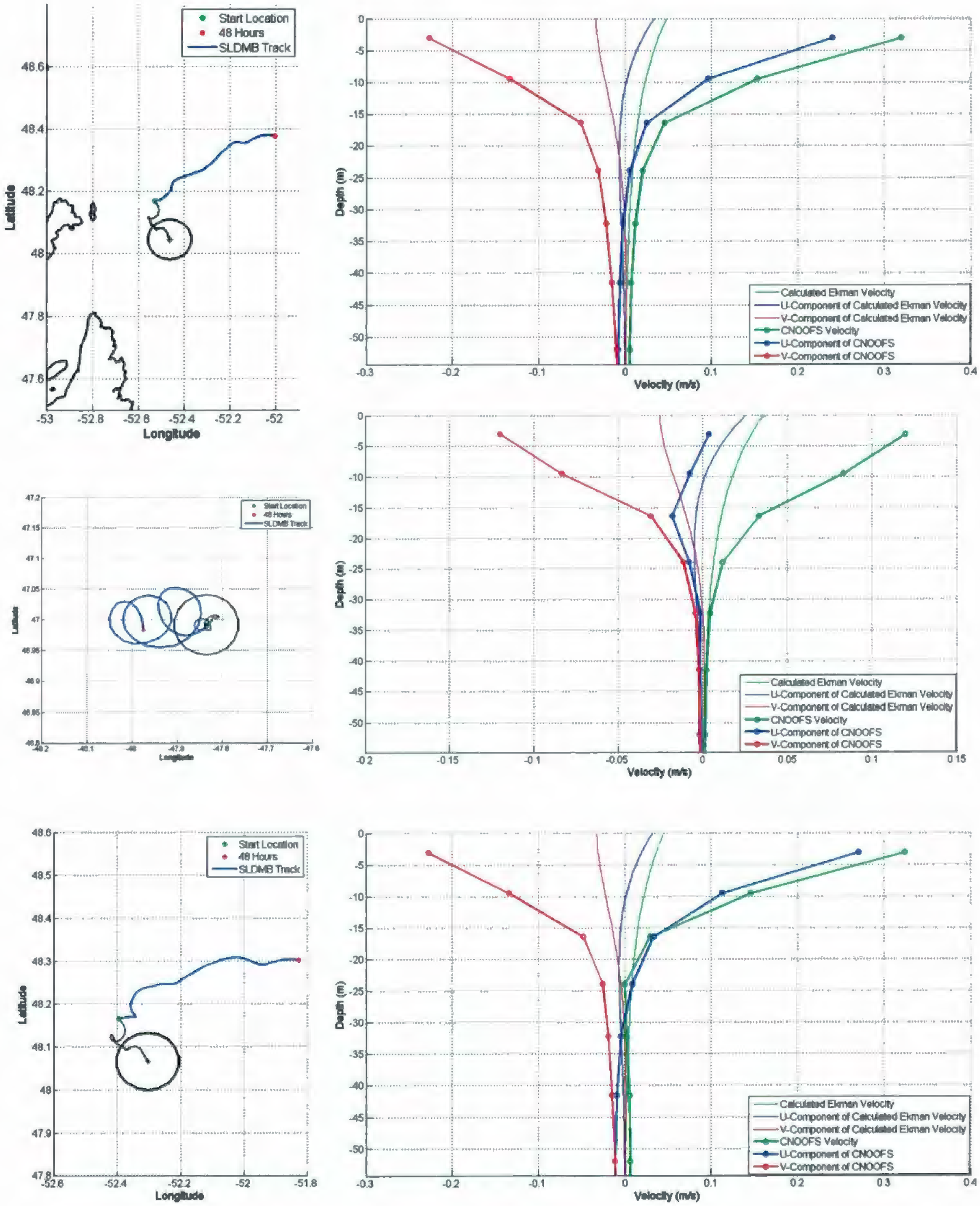

Figure 5.1 *Search trajectories and velocity profiles using CNOOFS currents for SLDMB 17303, 17316, and 17347.*
Column 1: Drifter trajectory and CANSARP Scientific Search trajectory over 48 hours
Column 2: Calculated velocity profile and CNOOFS current velocity profile comparison at start location of drift

The calculated Ekman velocities were small compared to the CNOOFS averaged velocities at 3m depth. This indicated that even with data extrapolation, surface velocity values for CNOOFS currents would change minimally from the velocities at the 3 m depth – certainly not significantly enough to account for the discrepancy between the present CANSARP output and the desired drift.

Of interest in this study was that not all velocity magnitude profiles behaved as anticipated (speed greater at surface than at depth). For example; at (40, -65), the 3 m speed of the CNOOFS currents were less near the surface than at a depth of ~ 95 m (about 0.03 m/s difference). Generally, current magnitude decreases with depth, and the surface layer speed would be higher than below the surface.

Figure 5.2 shows this profile, with the CNOOFS current velocity magnitudes offset such that they dissipate to 0 m/s at their last recorded point.

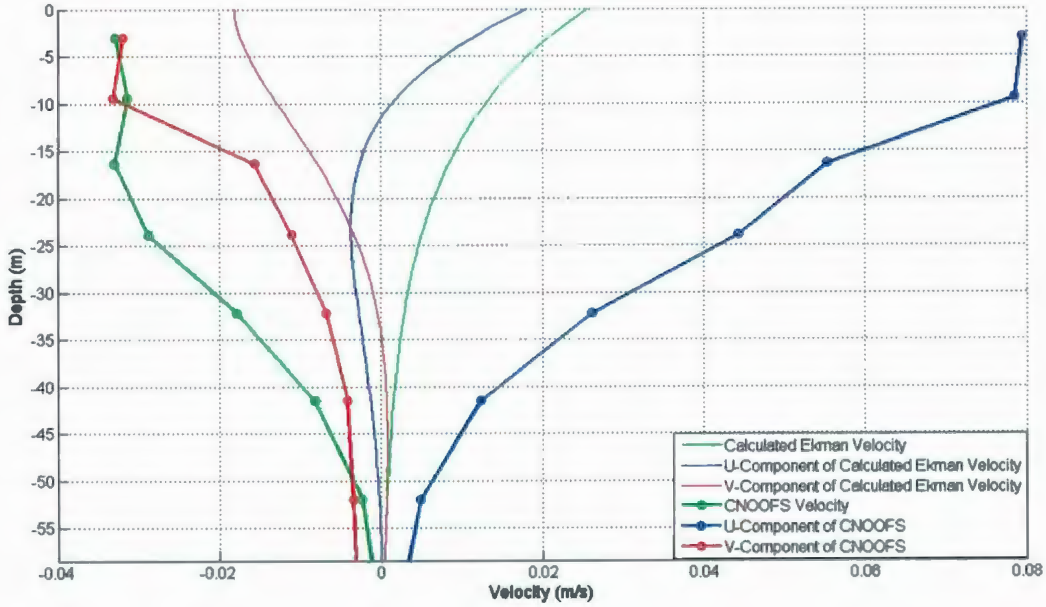

Figure 5.2 *Velocity magnitude profile using CNOOFS data for a simulation at point (40, -65).*

It should be noted that this experiment assumed constant vertical eddy diffusivity, and this may make the calculations inapplicable since this component becomes smaller near the surface layer of the ocean (Schaefer, 1973).

Overall, while this is not a conclusive study, it can be said that higher resolution in the depth of the current data may not necessarily improve the overall drift calculations in CANSARP Scientific.

5.1.2 Radius Determination

Another observation made upon examining drift and search trajectories of drifters was that drifts react with varying geographical location, and particularly similar were the drifter trajectories that were:

a) Near or on the continental shelf

b) Affected by eddies away from shelf

It was observed that the predictions made by CANSARP Scientific were of reasonable direction in both of the above cases, but the search trajectory was being underestimated. Drifters that did not fall into either of the above 2 categories were classified in a grouping of their own known as "all other drifters" for experimental purposes.

A possibility for these categories is to establish a search radius based on the oceanographic circulation characteristics related to their geographic location. At present, CANSARP and CANSARP Scientific both apply a "CANSARP Safety Factor" that increases with the iteration of the search attempt. This safety factor's purpose is to ensure the containment of the search object, based on elapsed time since primary search efforts were taken. For example, the first search's radius is multiplied by a factor of 1.1, the second by 1.6, the third by 2.0, etc. Each of these factors was determined experimentally when the MiniMax theory was first applied.

These factors are independent of the oceanographic environment the drift occurs in. Here we consider revamping the use of a constant safety factor to make it dependent on the oceanography in the particular geographical location. After a primary analysis of the 12 SLDMB drifters from August 2007 off the coast of Newfoundland, it was found that the radii of the drifters on or near the shelf (based on cumulative error of calculations) would have to increase by an overall average[5] of 7.9 times, or incorporate a safety factor of 8.7 in order to incorporate the search object. The radius of the search areas affected by eddies however, would only have to increase by 2.1 times overall, or apply a factor of 2.3 to successfully encompass these drifters. Of the three drifters in the "all other drifters" category, no consistent radius could be found. Successful encompassing of the drifter required anywhere from 3.2 to 7 times as large a radius. The possibility of further examining this group with a larger subset may lead to more detailed results.

While expanding a search radius by 7.9 times (producing an average search area of nearly 12000 km^2 and still only successfully retrieving an average of 40% of objects) is not feasible in most search cases (due to limited search unit availability/resources and time), implementing a larger radius combined with improved environmental inputs may lead to a higher search success rate. On the contrary, implementing a radius that is 2.1 times larger in regions exhibiting mesoscale eddies may be reasonable as the average search radius using this factor is 11 km, providing a total area to be searched of almost 400 km^2. As mentioned in Chapter 4, search time and the ability to cover an area in some reasonable time will depend on the available search units, their location at the time of the incident relative to the search area, their type, and the number available to complete the search plan.

[5] In this context, "overall average" refers to an average including the presently incorporated CANSARP Safety Factor

5.2 *Optimizing the Number of Particles used in the Monte Carlo Method*

Once validated, the Monte Carlo Method was explored in terms of both efficiency and productivity. One way to find a balance in both is to alter the number of particles used for simulations, since this is a user-controlled variable and is simple to change. In an effort to quantify the optimum number of particles for use in the Monte Carlo Method, a number of factors were considered:

1) The area covered
2) The length of time it takes to run each number of particles
3) What other countries use and why

It was established that both Norway (Breivik & Allen, 2008) and the United States' (Frost & Stone, 2001) outdated CASP model apply 500 particles in their search algorithms. The United States now allows an option of 3 modes entitled "fast," "normal," and "comprehensive." These options apply 2500, 5000, or 10,000 particles per scenario, respectively to allow the user to choose between speed of search planning and statistical validity. When cases have more unknowns, rapidly changing environmental conditions, or a long simulation time, normal or comprehensive simulations are usually carried out whereas most cases apply the "fast" mode in order to reduce processing time Northrop Grumman Space & Mission Systems Corporation, 2008).

At present, though it is modeled after the Norwegian version of Monte Carlo, the CANSARP Scientific implementation runs on 250 particles, by default.

As a benchmark, one drifter was used to test the length of time and the coverage of varying numbers of particles. Table 4 contains the results of these simulations over a 48 hour period using SLDMB 17324.

Table 4 Data from Monte Carlo Simulations over 48 Hours with SLDMB 17324 with Mercator Currents and Varying Numbers of Particles

Number of Particles	Length of Simulation on CANSARP Scientific (in seconds)	Maximum Radius Covered (in meters)
50	107.54	17001
100	149.13	20088
250	262.95	19572
500	492.61	16811
1000	1132.22	21165

These simulations can be compared to the same simulation using the MiniMax Method for the same amount of time with the same drifter. This experiment yields a search radius of 7421.2 m and a simulation time of 131.12 s.

To determine the maximum radius of the particles, the distance from end of the search trajectory to the furthest distributed particle was found. As the software functions now, it requires less time to run few than to run several. The radius increases somewhat regularly with the number of particles run.

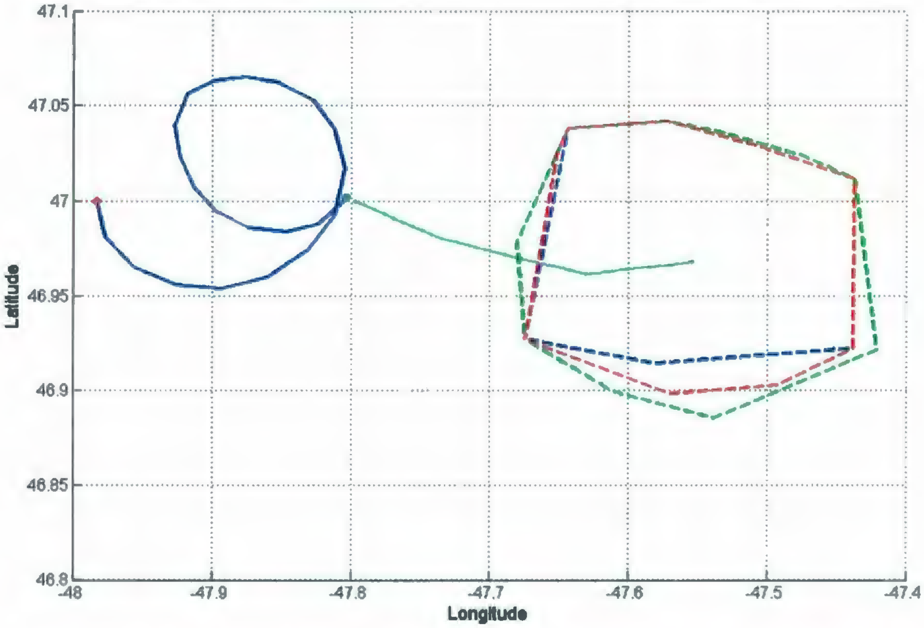

Figure 5.3 *Monte Carlo search areas with 1000 (green dashed line), 500 (red dashed line) and 250 (blue dashed line) particles after 24 hours for SLDMB 17303. Areas increase in size with the number of particles applied with values of 0.0183^{o2}, 0.0258^{o2}, and 0.0328^{o2}, respectively. The solid blue line is the SLDMB actual trajectory for 24 hours while the green dot represents the start of the drift and the red dot represents the end of the drift.*

While this method already provides a larger radius of search than the MiniMax Method, selecting the ideal number of points for use depends on the amount of time the search planner has, and the available resources. In time and produced search area, it appears from Figure 5.4 that running a simulation of 1000 particles is reasonable as the area is searchable and not drastically different from an area produced by 250 particles. This would require about 19 minutes to process, in addition to the search planner's task of assigning the search plan with tracks for the search and rescue units to follow.

Ideally, basing the number of particles run on the resources and time available for planning would be implemented in a manner similar to the USCG's approach where the weights of the statistical significance and time available are weighted in determining how many particles to apply. Selecting the number of particles based on the current behavior in a given region may be of use. For example, it would be useful to be able to select a higher number of particles for a simulation in a region where the currents are non-uniform and have small-scale detail, whereas in regions of more uniform motion, fewer particles could depict an equally useful search area. One proposal for future development would be to develop a benchmark value of convergence or divergence. Particle scattering in a region could be determined to converge or diverge based on its Root Mean Squared Error. If the value were larger than the benchmark value, the particles would be diverging and more particles could be applied to the search simulation. Similarly, if the RMS value were smaller than the benchmark, the particles would be converging and fewer particles would be required in the search simulation.

5.3 *Case Study: The Kiel Mooring*

On May 17, 2008 Researchers from Kiel University in Germany had a mooring set adrift from the slope east of the Strait of Belle Isle. It drifted from 53° 10' N, 50° 54' W on this day at approximately 18:00Z and moved slowly northeastward, then seaward, as per Figure 5.4.

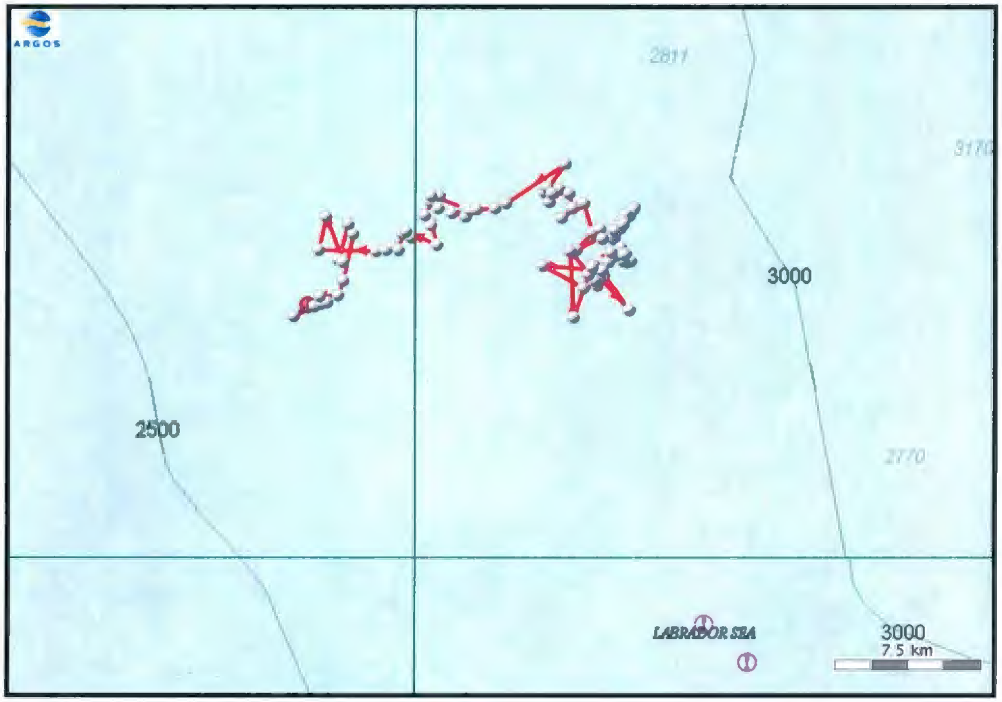

Figure 5.4 *Drift trajectory of lost mooring starting from 53° 10' N, 50° 54' W at 18:00Z on May 17, 2008. Reported locations illustrated from ARGO satellite fixes.*

On May 20, 2008, a notice was sent out from the Bedford Institute of Oceanography in Dartmouth, NS to a number of ocean forecast research groups requesting that if it were not a difficult task, to try to predict the trajectory of the mooring for retrieval on May 21 by the Canadian Coast Guard vessel, the CCG Hudson.

In an effort to assist this team, and to use this opportunity as validation for CANSARP Scientific, a simulation was completed using CNOOFS currents as shown in Figure 5.5 at 10 m depth. Simulations were also run at 50 m and 100 m depth, and yielded very similar results.

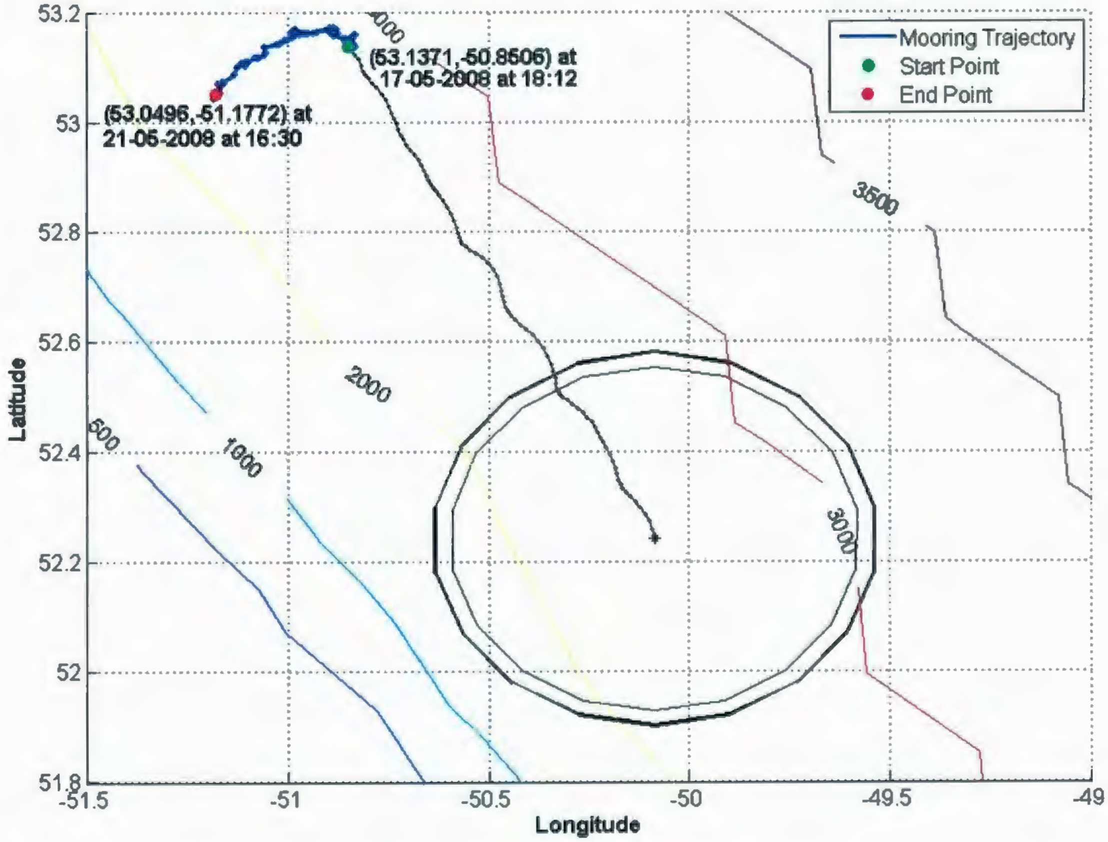

Figure 5.5 *Predicted trajectory of mooring from 18:12 on May 17, 2008 for 94.3 hours using CNOOFS currents at 10 m depth. Actual drift trajectory is in blue with start location at location at 94.3 hours noted. Search trajectory and area are plotted in black. Bathymetry is contoured by multi-colored lines and labeled according to their depth in meters.*

The predicted search trajectory follows the shelf break for the duration of the simulation whereas the mooring traveled almost perpendicular to this prediction. Since the LKP given for this case is in the Labrador Sea, it would be expected that the current in this region be strong enough to carry the mooring in the direction of the prevailing current, as the predicted trajectory goes. However, this was not the case, and further analysis was carried out to determine why.

Altimetry data obtained from the Aviso website (http://www.aviso.oceanobs.com) illustrated the daily averaged surface velocity fields (called gridded absolute dynamic velocities) and sea surface height (called gridded absolute geostrophic velocities). This data is merged from a number of satellites (Topex/Poseidon, ERS-2, Jason-1 and Envisat), and is represented on a 1/3° by 1/3° on the Mercator grid, available as daily averages. These velocities are computed using geostrophic method (Picaut and McPhadden, 1989). It is based on the assumption that the surface pressure gradient is balanced by Coriolis acceleration due to the surface flow. This method is reliable outside the equatorial area between 5° South and 5° North.

Figure 5.6 shows the same CANSARP Scientific simulation run with these velocities plotted as quivers, and the overall surface velocity field as contours.

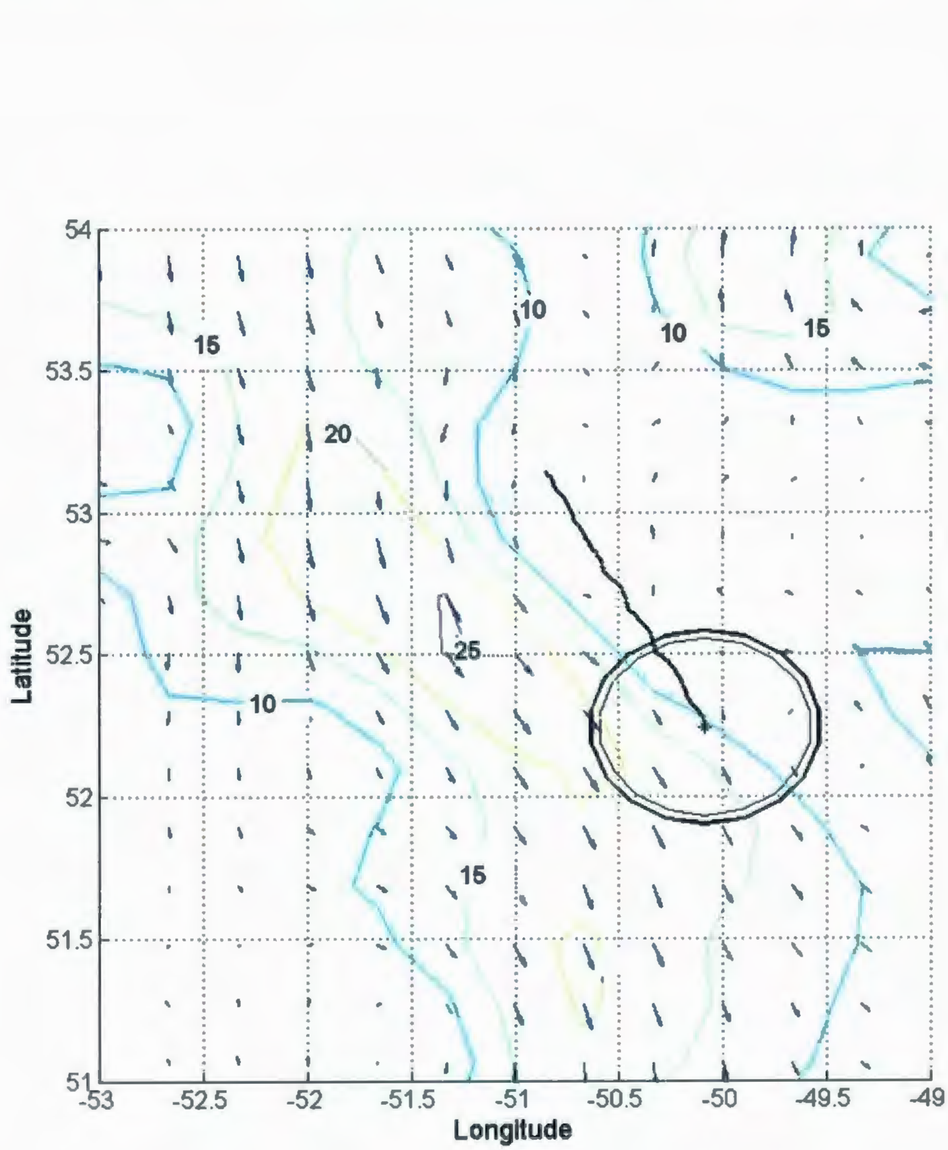

Figure 5.6 *CANSARP Scientific simulation on May 17, 2008 for 94.3 hours starting at 18:12:00 UTC run with CNOOFS currents with surface velocity field as quivers from AVISO altimetry data. Contours represent mean sea surface height in cm. Quivers represent sea surface velocity for the 17th of May. Black trajectory is the predicted drift trajectory by CANSARP Scientific and the circle is the proposed search area.*

While this figure verifies that the CANSARP Scientific search trajectory traveled with velocity of the currents for that simulation, no further insight is gained regarding the direction of travel of the mooring in question.

A daily plot of the mooring and its respective daily averaged sea surface height data was generated to explore relationships, as in Figure 5.7.

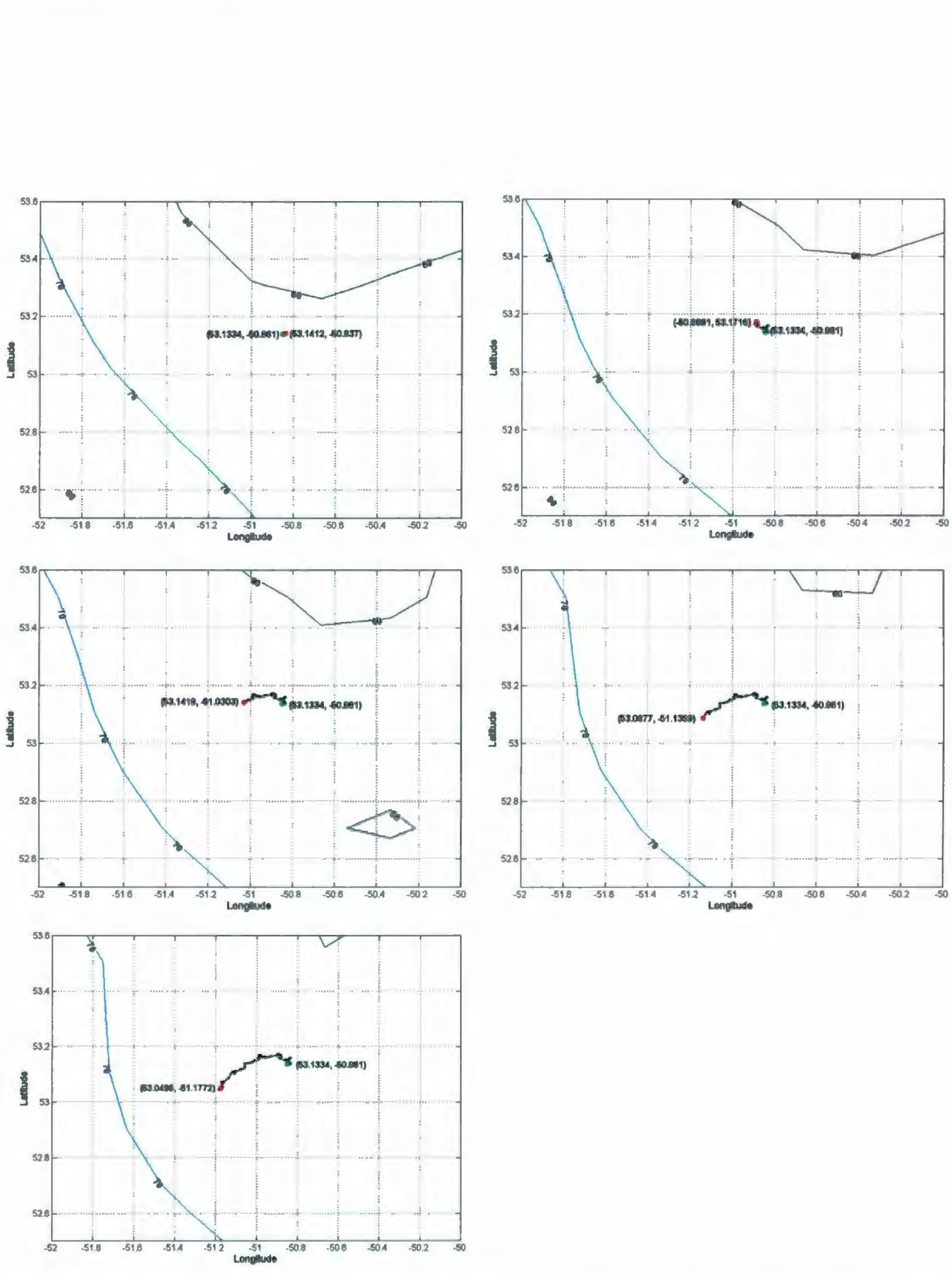

Figure 5.7 *Daily progression of mooring trajectory (black) with corresponding daily averaged sea surface height altimetry data on (L-R): a) May 17 , b) May 18, c) May 19, d) May 20, e) May 21. Drift trajectories are plotted from May 17 to end of day altimetry is plotted. The green dot indicates the mooring start location and the red dot indicates its last position on each day. Value of sea surface height is indicated on colored contours in units of cm.*

Figure 5.7 shows the mooring following movement of a water mass with a relatively low velocity west - southwestward. The sequence of sea surface height observations suggest that during this time, a meander may form and grow along the Labrador Current. The southwestward drift of the mooring follows the direction of fastest growth in this meander. Mesoscale meanders and eddies are energetic elements of ocean circulation and have spatial scales close to the internal Rossby Radius of Deformation. This radius changes as a function of the latitude and vertical stratification (Gill, 1982). In the Labrador Sea, the Internal Rossby Radius is about 20 km, whereas this value increases toward the equator to values of about 240 km (Chelton et al., 1997). While the effect of the mesoscale meander is seen in the altimetry data, neither geostrophic current (averaged over 1/3° by 1/3° squares nor the CNOOFS model output data are able to resolve motion under ~ 20 km diameter, as seen in the mooring's track (found to have a Rossby Radius of Deformation of about 11.2 km, according to an estimated calculation using Chelton et al.'s (1997) mapped gravity wave phase speed value at 47°) that is probably responsible for the tiny fluctuations in the actual trajectory as well as the overall direction of drift.

After the first day's drift, both the altimetry and CNOOFS data were reasonably able to explain the mooring's path, but because the drift simulation began in a poorly resolved region, CANSARP Scientific predicted day 1 in the incorrect direction, and so the following days were also predicted incorrectly, as a result of the initial error.

5.4 *Analysis of Errors Produced by CANSARP Scientific*

The observed mooring's behavior in the preceding case demonstrates that the CNOOFS model in CANSARP Scientific was not sufficiently accounting for certain small-scale behaviors in the ocean. These types of model errors are unavoidable in operational oceanographic applications because of the limits of the up-to-date ocean forecasting models. One way to account for this error in search predictions from CANSARP Scientific without more refined model data is to quantify the model error and model predictive skills and to use this information to optimize the Search and Rescue procedure.

This section presents results from an evaluation of CANSARP and CNOOFS predictive skills of SLDMB position. The purpose of this experiment was to evaluate the error of CANSARP scientific and CNOOFS predictions of the SLDMB positions. The model error for each case was quantified in an orthogonal local coordinate system that had one axis parallel to the local direction of the current and a second perpendicular axis. CANSARP Scientific was run for each of the 12 SLDMB drifters from August 2007 for each hour over a 48-hour period starting from the actual drifter location at each respective time. This was done (rather than starting from the computed location after each hour) so that the error calculated was not cumulative, but rather individual for each hour, in order to determine whether there was any consistent error between observations.

Figure 5.8 shows this result with a different color representing each drifter. The error in the position was calculated as:

$$(\varepsilon_{\parallel}, \varepsilon_{\perp}) = (\beta_{\parallel} - \beta_{\parallel_c}, \beta_{\perp} - \beta_{\perp_c}) \tag{5.3}$$

where $\varepsilon_{\parallel}$ is the error in the position in direction parallel of the surface model current, and $\varepsilon_{\perp}$ is the error in perpendicular direction, and β values represent points of the parallel and perpendicular vectors actual and computed (denoted by subscript 'C'), respectively.

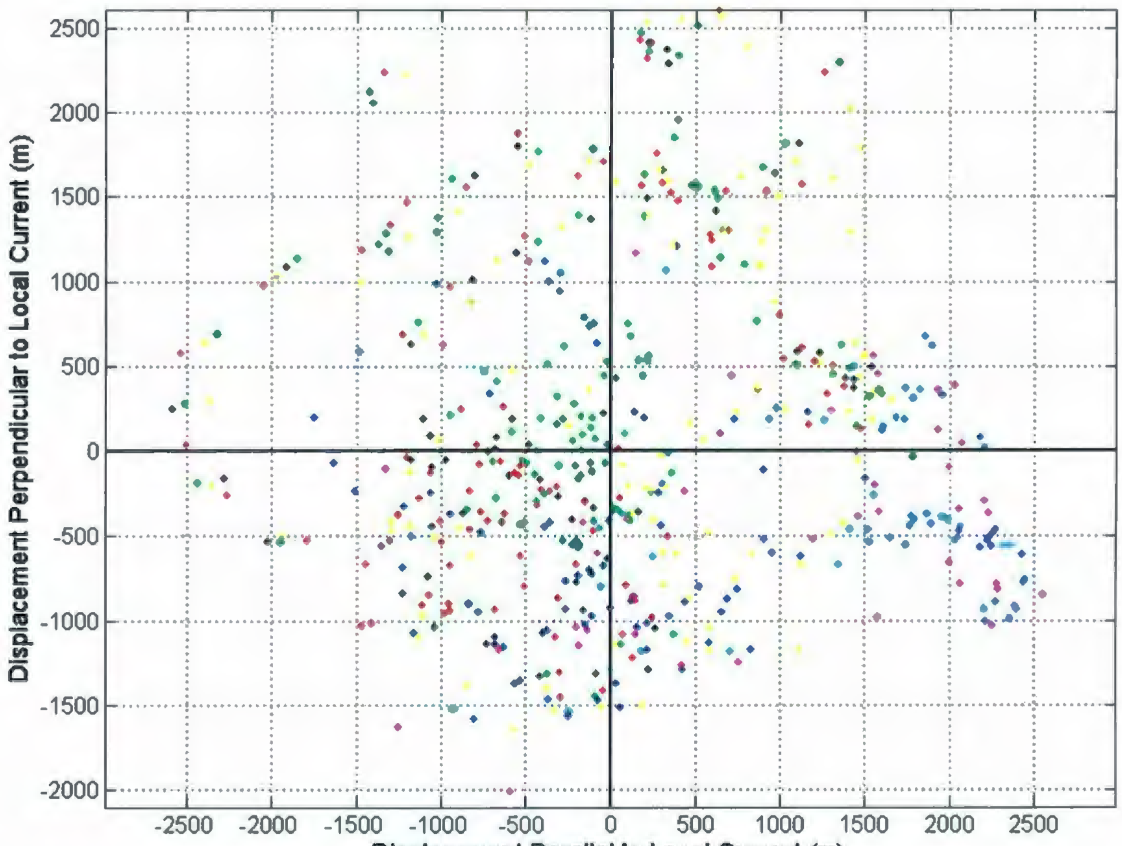

Figure 5.8 *Displacement calculations in the x and y directions where the current velocity is projected parallel and perpendicular to the local current in the region over a 48 hour period. Each of the 12 drifters explored are indicated by a different color dot in the plot. The mean displacement on this plot is (656.6991, 74.4230).*

Figure 5.9 shows the error in computed drifter positions. The predicted drifter positions include a large systematic error which is dominated by a negative component along the direction parallel to the local current. This in particular implies that the model underestimates the surface current velocity or that the predominant current pattern from the current model (CNOOFS) may be shifted left or right of the actual current pattern. It can also be said that the y-component of the error is usually positive, explaining that the floats tend to propagate right of the computed velocity. Figure 5.9 shows the error calculated as:

$$(\varepsilon_{\parallel}, \varepsilon_{\perp}) = \frac{(\beta_{\parallel} - \beta_{\parallel c}, \beta_{\perp} - \beta_{\perp c})}{|V_c|} \tag{5.4}$$

where V_c is calculated surface current velocity.

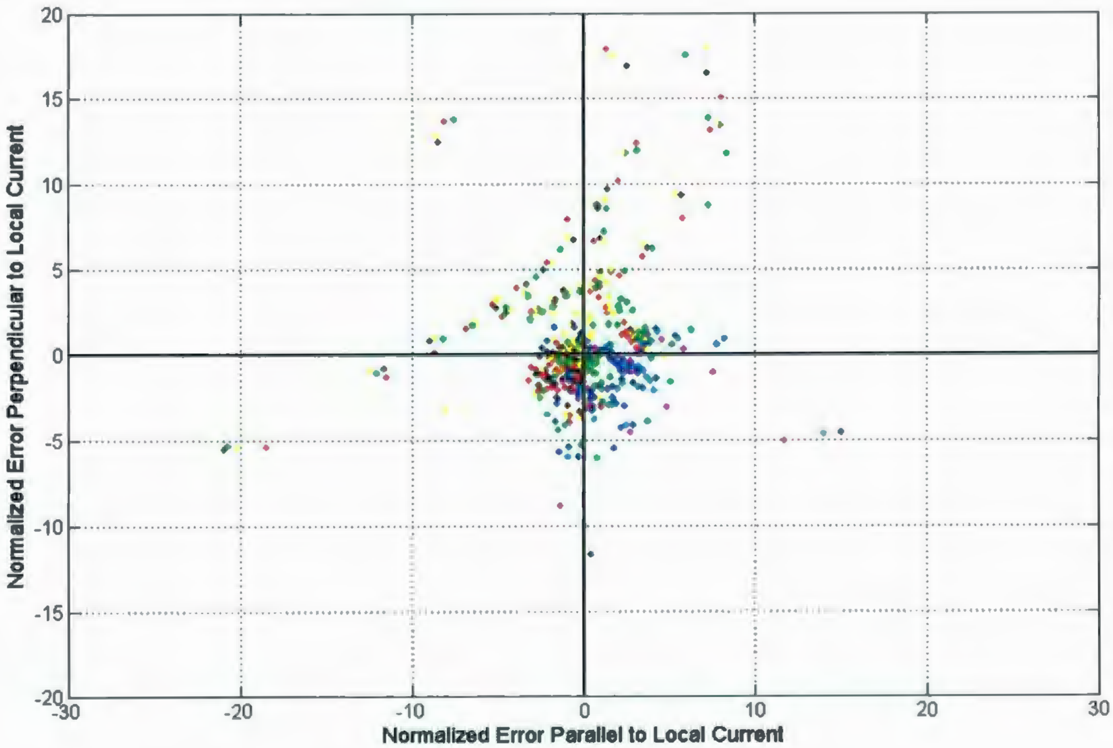

Figure 5.9 *Normalized error calculations in the x and y directions where the current velocity is projected parallel and perpendicular to the local current in the region over 48 hours. Each color dot represents the error produced by a different drifter. The mean error position is (-0.273, 1.52).*

The cloud of points in the plot of error is extended in the direction of predicted current velocity, suggesting that the errors related to the underestimation of current velocity the errors in the predicted drifter positions. Development of an approach to incorporate this error analysis in the planning of a Search and Rescue algorithm is the next step in this project.

Chapter 6 Conclusions

In this thesis, the CANSARP Scientific software was first tested and validated, with a number of minor changes made such that it would function properly. Once this task was completed, search methodologies in the United States and Norway were studied and compared to the existing MiniMax Method in Canada. Environmental datasets used in the CANSARP program were then explored in detail.

Based on the available data, the present MiniMax drift algorithms in both CANSARP and CANSARP Scientific were explored. In doing so, it was determined that all of the current estimation methods (Rule of Thumb, Ekman, and Madsen) underestimate the length of actual drifting buoys by 2.3 to 3 times, and inertial oscillations are overlooked. In response, the Pollard-Millard Method was programmed and tested in CANSARP Scientific. While this algorithm accounts for inertial oscillations, it does not necessarily replicate those oscillations produced by drifting buoys, and it still underestimates the total drift length by as much as the existing estimation methods. Possible reasons for this are that the climatological currents are a poor representation of the realistic current motion on the tested dates, the CMC GEM winds predictions are inaccurate for the tested dates, or that the validation of the wind data many be poor over water.

Next the CANSARP Scientific implementation of the Monte Carlo Method (modeled after the Norwegian seach program "LEEWAY") was investigated. Because this method has a stochastic component, it was thought that the search area produced by it would be more accurate than those from the MiniMax Methods. This was not the case as the predicted drift trajectory calculation is the same in MiniMax as Monte Carlo, and just the search area determination varies producing the same issue of length underestimation.

The most potential for future development was found when search simulations were run using model output data. In this thesis, CNOOFS and Mercator model output were applied in CANSARP Scientific. The direct application of this data to search simulations also produced underestimated trajectories in the majority of cases. At the surface, the CNOOFS data produced drift predictions of about 3 times shorter than the SLDMB trajectories, while the Mercator predictions were on an average of 2.7 times shorter. Because of the nature of the data (based on actual environmental inputs rather than a historical average), a number of adjustment possibilities were explored.

First a study was carried out that tested whether higher resolution in the CNOOFS model output data would improve the search prediction. This experiment was run since the CNOOFS model output files are depth-integrated and do not presently account for true surface velocity; a feature that was suspected to affect search prediction trajectories. A comparison was done by calculating the velocity components of Ekman's equations and plotting them against the actual CNOOFS data. This study was inconclusive, but the extrapolation of the CNOOFS velocity profiles to the surface layer indicate that even with a higher vertical resolution model, the velocities would not impact the drift prediction length considerably enough to correct the issue.

A second study explored the possibility of increasing the search area by a factor determined based on geography. Ideally this would be an excellent solution, but factors determined from this study indicated that the search radius would be unrealistic to cover in an average SAR mission. Further research into this idea may be useful for tweaking the safety factor applied.

A third experiment in an attempt to find a lost mooring provided the most insight regarding drift patterns in the North Atlantic Ocean. As a result of an inexplicable drift direction of the stranded mooring, altimetry (both sea surface velocity and height) data was obtained in efforts to find some subscale process that may have caused the unusual drift behavior. Although the altimetry displayed some general patterns of the current flow, the daily-averaged data was not refined enough to observe any anomalous processes. It is thought that the baroclinic structures that lead to velocities unresolved in the ocean forecast model may be one cause of this behavior, but no proof of this is found.

The real-life mooring experiment proved that the model resolution is not sufficient to represent all small scale behaviors in the ocean, and that even a transition from 1/4° to 1/12° model output data will probably not resolve many of these. In lieu of this, developing a search procedure that accounts for the errors characteristic of the model output would provide accurate enough search regions to find the search object. Resultantly a procedure was developed to calculate the model error of a dataset based on a known drifter dataset. This procedure can be applied to any model output data of current velocities before they are used in CANSARP, with the intention of incorporating this error into the search drift algorithm.

Overall, this thesis has provided insight into the shortcomings of the current Canadian Search and Rescue drift calculation theories, and has brought a new search concept based on model error determination into the forefront. With future work planned to implement an improved search approach based on error analysis of model currents into CANSARP Scientific, and to test it with a large drifter data set, it can be said that improvements are certainly in the works for the search theories that originated in the Second World War.

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Appendix A Running Cansarp Scientific

The CANSARP Scientific program is run from MATLAB™ and is designed to simulate the output of the CANSARP program of the Canadian Coast Guard Search and Rescue. Unlike the CANSARP program, CANSARP Scientific does not run from a Graphical User Interface (GUI), and settings have to be manually typed into functions, rather than selected from a list, as per CANSARP.

Within the 'cansarp_sim' folder for CANSARP Scientific, there is a folder called 'settings_scripts'. This folder contains three .m files that contain constant values and four .m files that can be edited according to a desired simulation. To set-up a simulation in CANSARP Scientific, the following procedure should be followed:

Select CANSARP Settings

In cansarp_settings.m file, the following settings must be adjusted according to the simulation of interest:

CANSARP_DRIFT_METHOD: Select 'MiniMax' or 'Monte Carlo' according to desired method. Default: 'MiniMax'.

CANSARP_DRIFT_INTERVAL: Time in hours to be used as time step for calculations. Default: 1.

CANSARP_SAFETY_FACTOR: A figure assigned to a search based on the succession of the attempt of the search. This number increases with each search attempt. Values based on table look-up in the National SAR Manual. Default: 1.1.

PREVIOUS_DRIFT_ERROR: Exists only if search is not first attempt. Drift error is cumulative for each search and is determined based on previous searches. Default: 0.

CANSARP_DRIFT_CONFIDENCE_FACTOR: Values of 0.125 or 0.3. It is assumed to be 0.125, unless there is very little known about the drift in question. Default: 0.3.

INITIAL_POSITION_ERROR: Based on the source of the LKP information. It is represented by "X" in the error calculations, and can be determined by table lookup in the National SAR Manual. Smallest possible value is 0.25 with a GPS. Default: 0.25*nautical_miles_to_metres.

SEARCH_UNIT_ERROR: Represented as "Y" in error calculations, it is the error associated with the means of searching, ranging from 5 to 15 M and can be looked up from a table in the National SAR Manual. Default: 0.25*nautical_miles_to_metres.

DISPLAY_FLAG: Set to 1 or 0 to determine whether CANSARP Scientific results are plotted. Default: 1.

CANSARP_V3_2_PLOT: Set to 1 or 0, indicates whether CANSARP Version 3.2 results are plotted, should they be available. Default: 0.

USE_WETCDF: Flag to determine whether NetCDF library is used; set to 1 or 0. Default: 1.

USE_PREVIOUS_CANSARP_FILE: Set to 1 or 0, indicates whether previously saved files are to be used in calculations. Default: 0.

SAVE_PLOT_OUTPUT: Set to 'no', 'iterative'. or 'last' such that no plots, each timestep plot, or just the final output plots are saved. Default: 'no'

MINIMAX_PLOT_TYPE: Set to 'all', 'last', 'half', or 'quarter' indicating the approximate number of iterations to plot. Default: 'all'.

MONTECARLO_PLOT_TYPE: Values of 'particles_on', 'particles_off', or 'particles_sidepaths_off' indicating all particles plotted, only average path (including mid, negative and positive paths) and search area plotted, or only average (mid) path and search area. Default: 'particles_on'.

Select Current Settings

In current_settings.m file, the following options exist:

CANSARP_USE_TWC: Boolean to indicate if total wind current is used (true) or if wind-driven and sea currents are used (false). Default: true.

CANSARP_CURRENT_TYPE: If CANSARP_USE_TWC is marked as true, option can be used to determine which current type to use. Options are 'constant', 'noofs' or 'mercator'. If CANSARP_USE_TWC is false, this variable is not used.

U_CURRENT_CONSTANT: If CANSARP_USE_TWC is true and CANSARP_CURRENT_TYPE is 'constant', then this variable can be used to specify manually the constant U current component. Default: 0 [m/s].

V_CURRENT_CONSTANT: If CANSARP_USE_TWC is true and CANSARP_CURRENT_TYPE is 'constant', then this variable can be used to specify manually the constant V current component. Default: 0.1 [m/s].

CANSARP_WIND_CURRENT_METHOD: Method to estimate wind current if CANSARP_USE_TWC is set to false. This variable is not used if CANSARP_USE_TWC is true. Possible values are 'rule of thumb', 'Ekman', 'Madsen', or new 'Pollard Millard'.

CURRENT_LEVEL: Added in the process of completing this project, CURRENT_LEVEL allows the user to select the depth of the current file being used according to the level number in the file. For CNOOFS and 1/4° Mercator, possible values are 1:46. For 1/12° Mercator, possible values are 1:50. The current file must be examined to see the depth that each level corresponds to. Default: 1.

Select Wind Settings

In wind_settings.m, the following options exist:

CANSARP_WINDS_TYPE.category: Numerical value for wind category, corresponding to the string in CANSARP_WINDS_TYPE.name.

CANSARP_WINDS_TYPE.name: String value for the wind category

Possible values:

1: Regional GRIB CMC file ('CMC GEM REGIONAL 15-km');
2: Global GRIB CMC file ('CMC GEM GLOBAL 0.9 deg');
3: CANSARP standard 2-degree CMC wind ('standard CANSARPV3.2 CMC 2 deg wind');
41: CNOOFS winds ('NOOFS')
42: CNOOFS winds with CSAR-wind ('NOOFS-wind + CSAR-wind')
5: CSAR-wind map and CMC REG GEM when available, old CMC wind otherwise ('CSAR-wind + CMC GEM REG');
6: Scatterometer winds, both ERS2 and QuickSCAT, and CMC REG GEM when available, old CMC wind otherwise ('scatterometers wind + CMC GEM REG');

61: QuickSCAT and CMC REG GEM when available, old CMC wind otherwise ('QuickSCAT wind + CMC GEM REG');
62: ERS2 and CMC REG GEM when available, old CMC wind otherwise ('ERS2 wind + CMC GEM REG');
99: Constant wind vector manually specified ('constant wind')

U_WIND_CONSTANT: Values for representing constant wind speed in m/s when CANSARP_WINDS_TYPE is 'constant wind' number 99. Otherwise ignored. Default value: 0.

V_WIND_CONSTANT: Values for representing constant wind speed in m/s when CANSARP_WINDS_TYPE is 'constant wind' number 99. Otherwise ignored. Default value: 10.

CSAR_WIND_MODEL: C-SAR wind processing approach if wind category involves CSAR wind map category number 5. Possible values: '2Dvar', 'CMOD', 'HPZV'. Default: '2Dvar'.

TIME_LIMIT_CSAR: C-SAR scene time acquisition, in days.
Default value: 2/24.

DISTANCE_LIMIT_CSAR: C-SAR Scene distance limit, in meters. Default value: 25 km (25*1000).

TIME_LIMIT_SCATT: Scatterometer scene time acquisition, in days. Default value: 2/24.

DISTANCE_LIMIT_SCATT: C-Scatterometer Scene distance limit, in meters. Default value: 100km (100*1000).

Update Path Settings

In path_settings.m, the path representing the data that is to be used for winds, currents, and field data must be specified to correspond to the selections made above before running CANSARP Scientific.

Running a Simulation

Once all of the settings are prepared, a simulation can be made in CANSARP Scientific. To run such a simulation, the following variables must be declared in a script or in the command line:

drift_filename:	Name of file containing drifter information. If none exists, 'NoDriftData.xxx' may be input.
drift_start_time:	The starting date and time of the drift, input as: datenum(yyyy,mm,dd,HH,MM,SS)
time_interval:	The total length of the drift in hours. If this is not input, the entire data from the field experiment is applied, if available.
drift_type:	Integer value corresponding to the drifter leeway type. Default: 1 for person in water. If this value exists, it is assumed that no field experiment data exists for the given drift number and that no ground truth data exists for the simulation.
drift_start_position:	The LKP for the drift given as [latitude longitude] in degrees.

Once these variables are declared, the following can be typed into the command line in MATLAB (for simplicity, a calling function was composed for this project):

[wind_drift, drifter] = cansarp_sim(drift_filename, drift_start_time, time_interval, drift_type, drift_start_position)

The results will yield a matrix of positions corresponding to the calculated drift expressed in the wind_drift variable and the drifter variable will contain a structure including information about the drifter in the simulation including its name, LKP position, LKP time, the number of errors associated with the simulation, any previous errors, and the total drift time of the simulation. A MATLAB figure is also produced if settings requested one, illustrating the drift of the simulation.

Appendix B Changes Made to the Monte Carlo Method in CANSARP Scientific

While no conceptual changes have been made to the Monte Carlo Method, some technical points have been altered in CANSARP Scientific:

- Vectorization of the number of particles run was applied and tested. In the original version of CANSARP Scientific, a loop exists such that for each particle that is seeded, all computations must be done on each particle. It was attempted to vectorize this process such that all particles undergo computations in a matrix, but time savings were minimal and the time to reprogram outweighed the benefit of vectorization.

- The scripts that were used to process the Monte Carlo Method using Mercator currents were edited such that only current files for new dates are loaded, rather than repeatedly loading the same files. This change resulted in notable time savings as seen in Figure B-1:

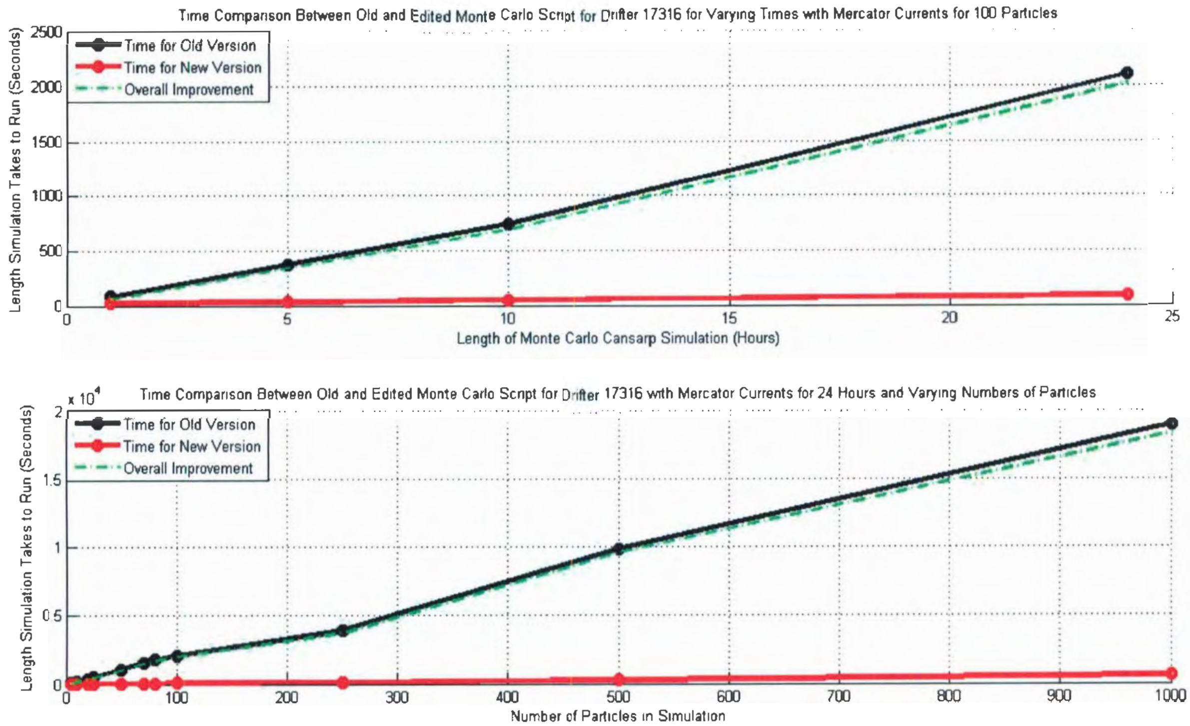

Figure B-1 *Time improvements made in Mercator Monte Carlo script by number of hours of simulation run and number of particles used.*

Appendix C General Changes Made to CANSARP Scientific

A major issue resolved within CANSARP Scientific throughout this validation was in the way that currents were extracted from the CNOOFS files. The current extraction method written for CANSARP Scientific was geared towards the Mercator currents which are structured on a regular grid as seen in Figure C-1. Applying this method to the CNOOFS currents of irregular grid resulted in values for currents that were sometimes in quite inaccurate locations, and thus produced incorrect drift simulations.

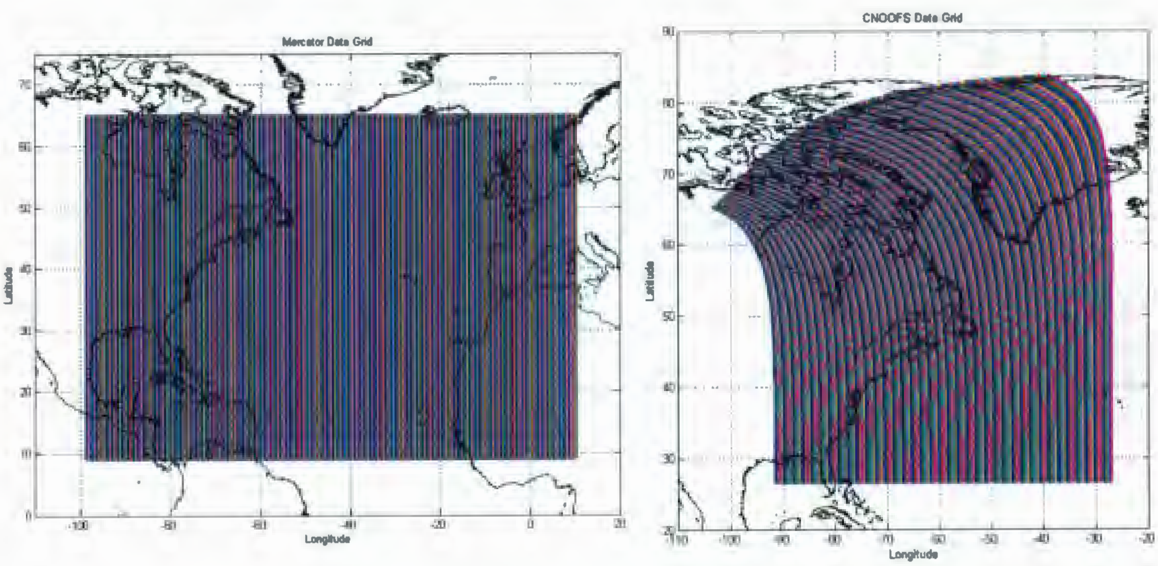

Figure C-1 *Regular Mercator grid and irregular CNOOFS grid.*

In the function called *get_sea_cnoofs.m*, a subgrid of the current data file was being extracted according to the coordinates a square box, which of course does not apply to the CNOOFS data. To resolve this issue, it has been programmed such that relative coordinates to the known position are determined, and the surrounding indices are then extracted.

A more general change implemented was the ability to select the level of the model output data file to use in running a CANSARP Scientific simulation. Previously, the only data that could be used was the surface level data (level 1), but now the number of the level can be selected by the user. It is important to note though, that this is not the depth of the current and to determine the depths that correspond to the levels, the data files must be opened and examined by the user.